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GRAVITY MODEL COMPARISON  
USING GEOS-I LONG ARC  
ORBITAL SOLUTIONS

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December 1967

GODDARD SPACE FLIGHT CENTER  
Greenbelt, Maryland

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SUMMARY

Satellite tracking data has been analyzed using three different sets of coefficients in the mathematical model that describes the earth's gravitational field. The results were not intended to be used as a definitive evaluation of the different coefficients but as an assessment of the effects that different sets of coefficients, station coordinates, and earth parameters that have been published, have on orbital geodetic results.

Orbital solutions were estimated from optical tracking data from the GEOS-I satellite, taken by five major geodetic optical tracking networks. The networks and camera types consisted of the SAO Baker-Nunn, GSFC STADAN and SPEOPT MOTS 40" and 24", USAF PC-1000, and the US C&GS BC-4. The three sets of gravity coefficients used were the SAO M-1 set (modified by the GEOS-I resonant harmonics), APL 3.5 set, and the NWL 5E-6 set. The semi-major axis, gravitational constant, and flattening consistent with each set of coefficients were also used. The station coordinates used were referenced to the SAO C-5 standard earth as no other complete set of optical station coordinates were available.

Several long arc orbital analyses were completed using each set of coefficients and the results were compared. Orbits were fitted to two overlapping

data sets; the arc lengths of these orbits were 5-1/4 days and 1 day. The orbital solutions obtained with each set of coefficients were compared. Furthermore, the trajectory differences were computed, and were resolved into radial, cross track and along track components. The along track differences were as great as 400 meters for the 5-1/4 day arc and 200 meters for the 1 day arc.

The range measurements of the Goddard Range and Range Rate (GRARR) S-Band Tracking System at Rosman were evaluated for 15 passes recorded during the first week in January 1966. The actual measurements were compared with values computed from the optical orbital solutions previously mentioned. The residual differences between the observed and computed ranges were analyzed for zero set range bias errors, timing errors, and random errors. The error estimates obtained from the orbital solutions determined using the SAO M-1 gravitational coefficients displayed a much greater degree of consistency from pass to pass. Also, the error estimates obtained from the 5-1/4 day arc were in good agreement with those obtained from the 1 day arc when the SAO M-1 coefficients were used but agreement was generally poor when the reference orbits were determined using the NWL 5E-6 and APL 3.5 gravitational coefficients.

Two estimates of the coordinates for the Goddard Range and Range Rate station in Tananarive, Madagascar were obtained from independent data sets using each set of coefficients. Only the SAO M-1 set produced two estimates that were consistent; they differed by only 5 meters.

These comparisons serve to reinforce what was intuitively obvious — that for long arc geodetic work, the most complete set of gravity coefficients together with consistent station coordinates should be used.

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LIST OF ABBREVIATIONS

|        |  |
|--------|--|
| APL    | Applied Physics Laboratory of Johns Hopkins University |
| GSFC   | Goddard Space Flight Center                            |
| MOTS   | Minitrack Optical Tracking System                      |
| NWL    | Naval Weapons Laboratory                               |
| SAO    | Smithsonian Astrophysical Observatory                  |
| SPEOPT | Special Optical Tracking System                        |
| STADAN | Satellite Tracking and Data Acquisition Network        |
| USAF   | United States Air Force                                |
| USC&GS | United States Coast and Geodetic Survey                |

GRAVITY MODEL COMPARISON  
USING GEOS-I LONG ARC  
ORBITAL SOLUTIONS

## 1.0 INTRODUCTION

This report presents results and comparisons that have been obtained from the reduction of satellite tracking data using three different sets of coefficients in the mathematical model that describes the earth's gravitational field. These comparisons were not intended as an evaluation of the coefficients but as an assessment of the effects of using the different sets in order to choose the most suitable available set of gravity coefficients and station coordinates for long arc (greater than 6 revolutions) geodetic purposes.

These results were obtained using the orbit determination program NONAME (Reference 1), and the orbital solutions were estimated from optical tracking data taken from the GEOS-I satellite. The NONAME program uses a mathematical function based on Legendre polynomials to approximate the earth's gravitational field (Appendix A). Several sets of coefficients for these polynomials have been published; three of these sets were used for this work; they are:

1. The SAO M-1 Set. Modified by the GEOS-I Resonant Harmonics ( $C_{13,12}$ ,  $C_{14,12}$ ,  $C_{15,12}$ ,  $S_{13,12}$ ,  $S_{14,12}$ ,  $S_{15,12}$ ) (Reference 2), (Reference 7).
2. The APL 3.5 Set (Reference 3).
3. The NWL 5E-6 Set (Reference 4).

These are presented in Table II.

For the purposes of these comparisons, the earth's semi-major axis, gravitational constant, and flattening coefficient that are consistent with each set of coefficients were used. These are summarized in Table I. The station coordinates were unchanged and were referenced to the SAO C-5 standard earth (Appendix C), since no other complete set of coordinates for the optical tracking stations was available.

The use of only the one set of station coordinates prevents these results being used as any sort of definitive evaluation of these sets of gravity coefficients. It should be noted, however, that the ellipsoids defined by the parameters in Table I are very similar; thus the station coordinates, if they are fairly

Table I  
Parameters for the Earth's Ellipsoid

| Parameter \ Model                                     | SAO M-1                | APL 3.5                | NWL 5E-6                |
|---|------------------------|------------------------|-------------------------|
| Gravitational Constant ( $\text{km}^3/\text{sec}^2$ ) | $3.986032 \times 10^5$ | $3.986075 \times 10^5$ | $3.9860542 \times 10^5$ |
| Semi-Major Axis (km)                                  | 6378.165               | 6378.166               | 6378.165                |
| Flattening  | $\frac{1.}{298.25}$    | $\frac{1.}{298.30}$    | $\frac{1.}{298.25}$     |

Table II  
Harmonic Coefficients (Normalized)

| n m | SAO M1                |                       | APL 3.5               |                       | NWL 5E-6              |                       |
|-----|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|     | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ |
| 2 0 | -484.1735             |                       | -484.198              |                       | -484.194              |                       |
| 2 1 |                       |                       |                       |                       | 0.016                 | 0.062                 |
| 2 2 | 2.379                 | -1.351                | 2.381                 | -1.198                | 2.446                 | -1.519                |
| 3 0 | 0.9623                |                       | 1.011                 |                       | 0.984                 |                       |
| 3 1 | 1.936                 | 0.266                 | 1.84                  | 0.215                 | 2.148                 | 0.274                 |
| 3 2 | 0.734                 | -0.538                | 1.219                 | -0.6791               | 0.978                 | -0.906                |
| 3 3 | 0.561                 | 1.620                 | 0.6609                | 0.9795                | 0.585                 | 1.625                 |
| 4 0 | 0.5497                |                       | 0.467                 |                       | 0.507                 |                       |
| 4 1 | -0.572                | -0.469                | -0.5624               | -0.4403               | -0.495                | -0.575                |
| 4 2 | 0.330                 | 0.661                 | -0.4179               | 0.4438                | 0.274                 | 0.671                 |

Table II (Continued)

| n<br>m | SAO M1                |                       | APL 3.5               |                       | NWL 5E-6              |                       |
|--------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|        | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ |
| 4 3    | 0.851                 | -0.190                | 0.8464                | 0.007062              | 1.030                 | -0.247                |
| 4 4    | -0.053                | 0.230                 | -0.2106               | 0.1898                | -0.413                | 0.336                 |
| 5 0    | -0.0633               |                       | 0.084                 |                       | 0.045                 |                       |
| 5 1    | -0.079                | -0.103                | 0.1370                | -0.1669               | 0.032                 | -0.119                |
| 5 2    | 0.631                 | -0.232                | 0.2684                | -0.3379               | 0.637                 | -0.328                |
| 5 3    | -0.520                | 0.007                 | 0.09131               | 0.1035                | -0.389                | -0.124                |
| 5 4    | -0.265                | 0.064                 | -0.4884               | -0.260                | -0.549                | 0.148                 |
| 5 5    | 0.156                 | -0.592                | -0.03358              | -0.6686               | 0.215                 | -0.594                |
| 6 0    | -0.1792               |                       | -0.103                |                       | -0.219                |                       |
| 6 1    | -0.047                | -0.027                | -0.0002093            | 0.1009                | -0.085                | 0.192                 |
| 6 2    | 0.069                 | -0.366                | -0.1610               | -0.1555               | 0.129                 | -0.457                |
| 6 3    | -0.054                | 0.031                 | 0.5303                | 0.05111               | -0.020                | -0.134                |
| 6 4    | -0.044                | -0.518                | -0.3069               | -0.5087               | -0.193                | -0.316                |
| 6 5    | -0.313                | -0.458                | -0.18                 | -0.5091               | -0.093                | -0.786                |
| 6 6    | -0.040                | -0.155                | 0.01434               | -0.2316               | -0.324                | -01360                |
| 7 0    | -0.0860               |                       | 0.153                 |                       | 0.105                 |                       |
| 7 1    | 0.197                 | 0.156                 | 0.1261                | 0.09355               | 0.331                 | 0.083                 |
| 7 2    | 0.364                 | 0.163                 | 0.4586                | 0.05998               | 0.350                 | -0.195                |
| 7 3    | 0.250                 | 0.018                 | 0.3938                | -0.2067               | 0.323                 | 0.045                 |
| 7 4    | -0.152                | -0.102                | -0.1368               | 0.0004798             | -0.467                | -0.244                |
| 7 5    | 0.076                 | 0.054                 | -0.05682              | -0.1871               | 0.055                 | 0.021                 |
| 7 6    | -0.328                | 0.063                 | -0.4552               | 0.758                 | -0.477                | -0.244                |
| 7 7    | 0.055                 | 0.096                 | 0.08840               | -0.1443               |                       |                       |

Table II (Continued)

| n  | m  | SAO M1                |                       | APL 3.5               |                       | NWL 5E-6              |                       |
|----|----|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|    |    | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ |
| 8  | 0  | 0.0655                |                       | 0.170                 |                       |                       |                       |
| 8  | 1  | -0.075                | 0.065                 | -0.1481               | -0.04843              |                       |                       |
| 8  | 2  | 0.026                 | 0.039                 | 0.09472               | -0.03764              |                       |                       |
| 8  | 3  | -0.037                | 0.004                 | -0.05497              | 0.2168                |                       |                       |
| 8  | 4  | -0.212                | -0.012                | -0.06901              | 0.03761               |                       |                       |
| 8  | 5  | -0.053                | 0.118                 | 0.08040               | -0.002495             |                       |                       |
| 8  | 6  | -0.017                | 0.318                 | -0.02193              | 0.6658                |                       |                       |
| 8  | 7  | -0.0087               | 0.031                 | 0.1697                | -0.07009              |                       |                       |
| 8  | 8  | -0.248                | 0.102                 | -0.1457               | 0.09424               |                       |                       |
| 9  | 0  | 0.0122                |                       | 0.041                 |                       |                       |                       |
| 9  | 1  | 0.117                 | 0.012                 |                       |                       |                       |                       |
| 10 | 00 | 0.0118                |                       |                       |                       |                       |                       |
| 10 | 01 | 0.105                 | -0.126                |                       |                       |                       |                       |
| 10 | 02 | -0.105                | -0.042                |                       |                       |                       |                       |
| 10 | 03 | -0.065                | 0.030                 |                       |                       |                       |                       |
| 10 | 04 | -0.074                | -0.111                |                       |                       |                       |                       |
| 11 | 00 | -0.0630               |                       | 0.104                 |                       |                       |                       |
| 11 | 01 | -0.053                | 0.015                 |                       |                       |                       |                       |
| 12 | 00 | 0.0714                |                       | 0.062                 |                       |                       |                       |
| 12 | 01 | -0.163                | -0.071                |                       |                       |                       |                       |
| 12 | 02 | -0.103                | -0.0051               |                       |                       |                       |                       |
| 12 | 12 | -0.031                | 0.0008                |                       |                       |                       |                       |

Table II (Continued)

| n<br>m | SAO M1                |                       | APL 3.5               |                       | NWL 5E-6              |                       |
|--------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|        | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ | $\bar{C} \times 10^6$ | $\bar{S} \times 10^6$ |
| 13 00  | 0.0219                |                       |                       |                       |                       |                       |
| 13 12  | -0.06769              | 0.06245               |                       |                       |                       |                       |
| 13 13  | -0.059                | 0.077                 | -0.4689               | 0.04748               | -0.03                 | 0.11                  |
| 14 00  | -0.0332               |                       |                       |                       |                       |                       |
| 14 01  | -0.015                | 0.0053                |                       |                       |                       |                       |
| 14 11  | 0.0002                | -0.0001               |                       |                       |                       |                       |
| 14 12  | 0.00261               | -0.02457              |                       |                       |                       |                       |
| 14 14  | -0.014                | -0.003                | -0.06368              | -0.037                |                       |                       |
| 15 09  | -0.0009               | -0.0018               |                       |                       |                       |                       |
| 15 12  | -0.07473              | -0.01026              |                       |                       |                       |                       |
| 15 13  | -0.058                | -0.046                |                       |                       | -0.06                 | -0.06                 |
| 15 14  | 0.0043                | -0.0211               | 0.00087843            | -0.0101               | 0.01                  | -0.03                 |

accurately determined with reference to the center of mass, as the SAO C-5 coordinates are generally accepted to be, should not introduce any large differences in the results.

Several long arc analyses were completed using each set of coefficients in turn, and the results have been compared; these are discussed in some detail in Sections 3.0 - 6.0.

## 2.0 DESCRIPTION OF THE EARTH'S GRAVITATIONAL FIELD

The earth's geopotential can be approximated by the following mathematical model:

$$U = \frac{GM}{r} \left\{ 1 + \sum_{n=2}^k \sum_{m=0}^n \left(\frac{a}{r}\right)^n p_n^m (\sin \phi) [C_{nm} \cos m\lambda + S_{nm} \sin m\lambda] \right\} \quad (1)$$

where

$G$  is the universal gravitational constant,

$M$  is the mass of the earth,

$r$  is the geocentric satellite distance,

$a$  is the earth's mean equatorial radius,

$\phi$  is the sub-satellite geocentric latitude,

$\lambda$  is the sub-satellite east longitude,

$p_n^m (\sin \phi)$  are the associated Legendre polynomials of degree  $n$  and order  $m$ ,

and

$C_{nm}$ ,  $S_{nm}$  are the denormalized gravitational coefficients.

The denormalized gravitational coefficients are related to the normalized coefficients  $(\bar{C}_{nm}, \bar{S}_{nm})$  as indicated below:

$$C(n,m) = [(n-m)! (2n+1) K / (n+m)!]^{1/2} \bar{C}(n,m)$$

$$S(n,m) = [(n-m)! (2n+1) K / (n+m)!]^{1/2} \bar{S}(n,m)$$

where,

$$K = 1 \text{ when } m = 0$$

$$K = 2 \text{ when } m \neq 0$$

The geopotential formulated in this manner can be converted into gravitational accelerations in inertial coordinates  $(x, y, z)$  as follows:

$$\ddot{\mathbf{x}}_o = \frac{\partial \mathbf{u}}{\partial \mathbf{r}} \frac{\partial \mathbf{r}}{\partial \mathbf{x}} + \frac{\partial \mathbf{u}}{\partial \phi} \frac{\partial \phi}{\partial \mathbf{x}} + \frac{\partial \mathbf{u}}{\partial \lambda} \frac{\partial \lambda}{\partial \mathbf{u}},$$

where the subscript "o" denotes accelerations due to the earth's gravitational field. Similar expressions hold for  $\ddot{\mathbf{y}}_o$  and  $\ddot{\mathbf{z}}_o$ . The NONAME program uses a model in this form to compute the accelerations due to the earth's gravitational field.

The three different sets of harmonic coefficients (normalized) and associated earth parameters used in this analysis are shown in Tables I and II. The SAO M-1 is the largest set with a total of 122 coefficients; the APL 3.5 set has 84 coefficients and the NWL 5E-6 set has 64. Of these three sets, only the SAO M-1 set has GEOS-I resonant terms (harmonics of order 12).

The SAO M-1 set was determined using optical observations from a number of satellites, and the other two sets were determined from Tranet Doppler observations, again from a number of satellites.

### 3.0 DIFFERENCES IN ORBITAL SOLUTIONS

Orbits were fitted to two data sets from the first week in January 1966, and the arc lengths of these orbits were 5-1/4 days and 1 day. The 5-1/4 day arc covered the period from 01 hrs. GMT on December 31, 1965 to 06 hrs., January 5, 1966, and the data set consisted of 1057 optical observations.\* The 1 day arc covered the period from 06 hrs., January 2, 1966, to 08 hrs., January 3, 1966. This data was a subset of the 5-1/4 day arc data set and consisted of 444 optical observations. These data sets are summarized in Table III.

The root mean squares of the observations about the orbital solutions were computed and these are shown in Table IV. The r.m.s. values were lower for the orbits fitted using the SAO M-1 set for both arcs. The differences between the observed measurements and values computed from the orbital solutions were computed and plotted on histograms; these are shown in Figures 1-4. The right ascension residuals shown in the Figures have been multiplied by the cosine of the corresponding declination measurement to account for the degradation of the measurements recorded when the declination value was large. These Figures clearly indicate that the orbital solutions obtained with the SAO M-1 set of coefficients fit the data sets better than the other solutions. This is especially true

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\*Right ascension plus declination measurements.

Table III  
Summary of Optical Measurements By Station

| Network                   | Station | Camera Type  | No. of Observations |           |
|---------------------------|---------|--------------|---------------------|-----------|
|                           |         |              | 5-1/4 Day Arc       | 1 Day Arc |
| SAO                       | 1ORGAN  | Baker-Nunn   | 2                   |           |
|                           | 1JUPTR  | "            | 26                  | 26        |
|                           | 1NATOL  | "            | 8                   | 2         |
|                           | OSLONR  | "            | 4                   |           |
|                           | AUSBAK  | "            | 4                   |           |
|                           | 1SHRAZ  | "            | 2                   | 2         |
|                           | 1SPAIN  | "            | 6                   |           |
|                           | 1TOKYO  | "            | 12                  | 4         |
|                           | 1VILDO  | "            | 2                   |           |
|                           | 1MAUIO  | "            | 2                   |           |
|                           | AGASSI  | Geodetic 36" | 10                  |           |
| Total:                    |         |              | 78                  | 34        |
| SPEOPT                    | 1COLBA  | MOTS 40"     | 164                 | 71        |
|                           | 1JUM40  | "            | 22                  | 16        |
|                           | 1BERMD  | "            | 84                  | 36        |
|                           | 1PURI0  | "            | 14                  |           |
|                           | 1DENVR  | "            | 70                  | 14        |
|                           | 1JUM24  | MOTS 24"     | 26                  | 24        |
| Total:                    |         |              | 380                 | 158       |
| STADAN                    | 1FTMYR  | MOTS 40"     | 82                  | 54        |
|                           | 1BPOIN  | "            | 53                  |           |
|                           | 1GFORK  | "            | 26                  | 9         |
|                           | 1MOJAV  | "            | 25                  | 25        |
|                           | Total:  |              | 186                 | 91        |
| USAF                      | HUNTER  | PC-1000      | 59                  | 47        |
|                           | SWANIS  | "            | 14                  | 14        |
|                           | GRDTRK  | "            | 7                   |           |
|                           | ANTIGA  | "            | 26                  |           |
|                           | SEMMES  | "            | 60                  | 36        |
|                           | CURACO  | "            | 40                  | 26        |
|                           | HOMEST  | "            | 94                  | 24        |
|                           | JUPRAF  | "            | 17                  | 17        |
|                           | BEDFRD  | "            | 22                  |           |
|                           | ABERDN  | "            | 74                  |           |
| Total:                    |         |              | 413                 | 164       |
| Total of All Observations |         |              | 1,057               | 444       |

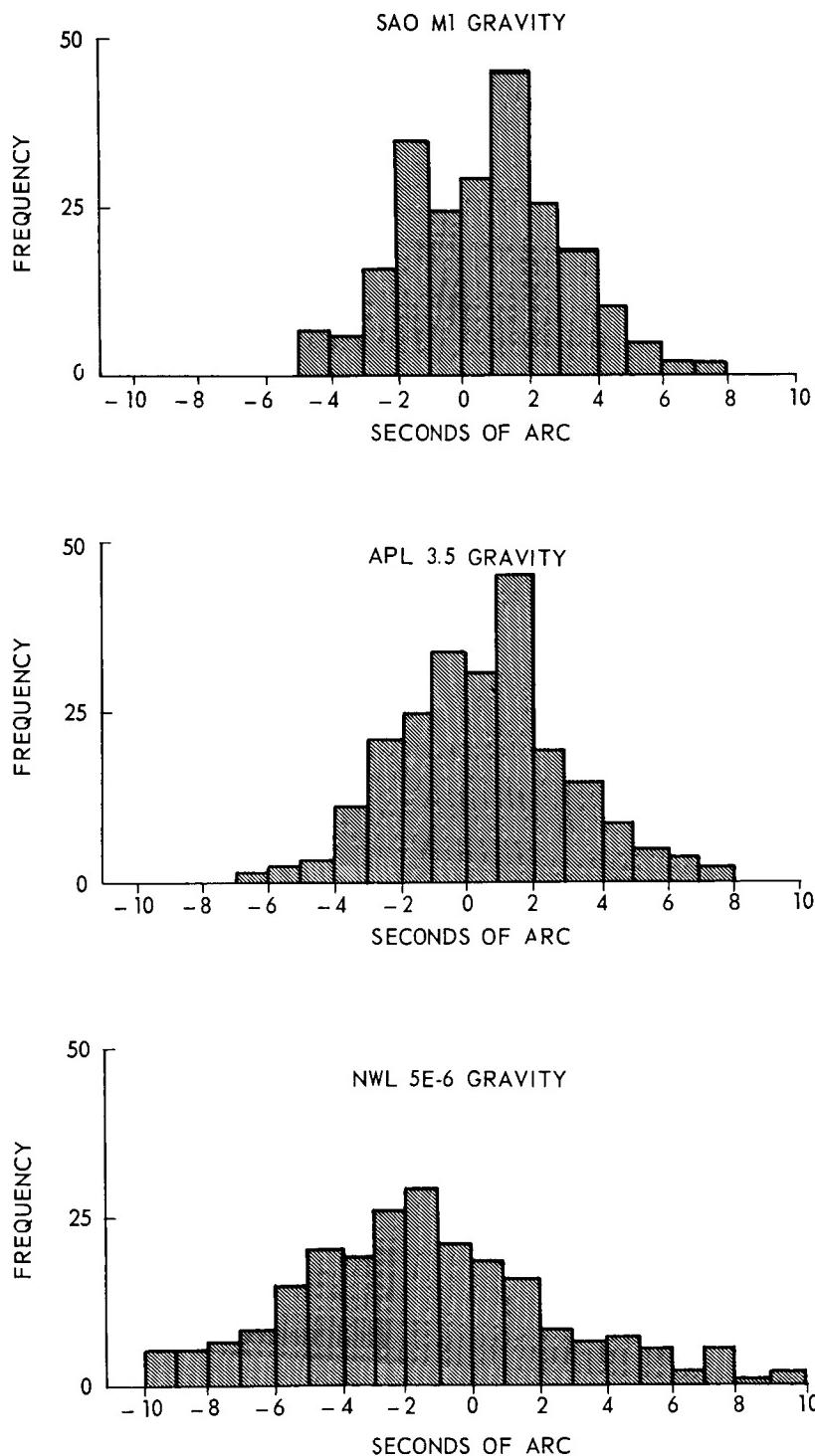


Figure 1. Right Ascension Residuals from 1 Day Arc

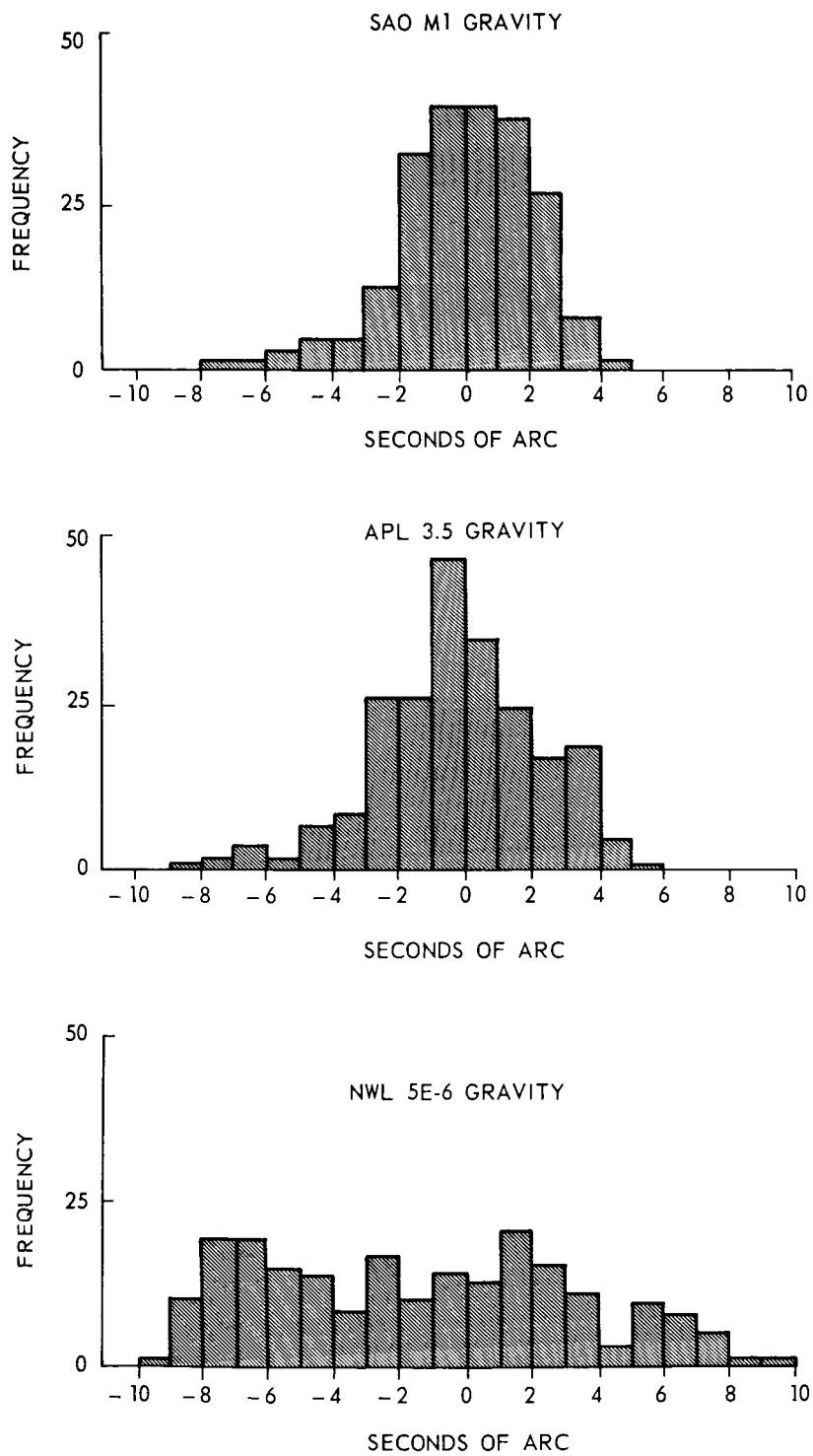


Figure 2. Declination Residuals from 1 Day Arc

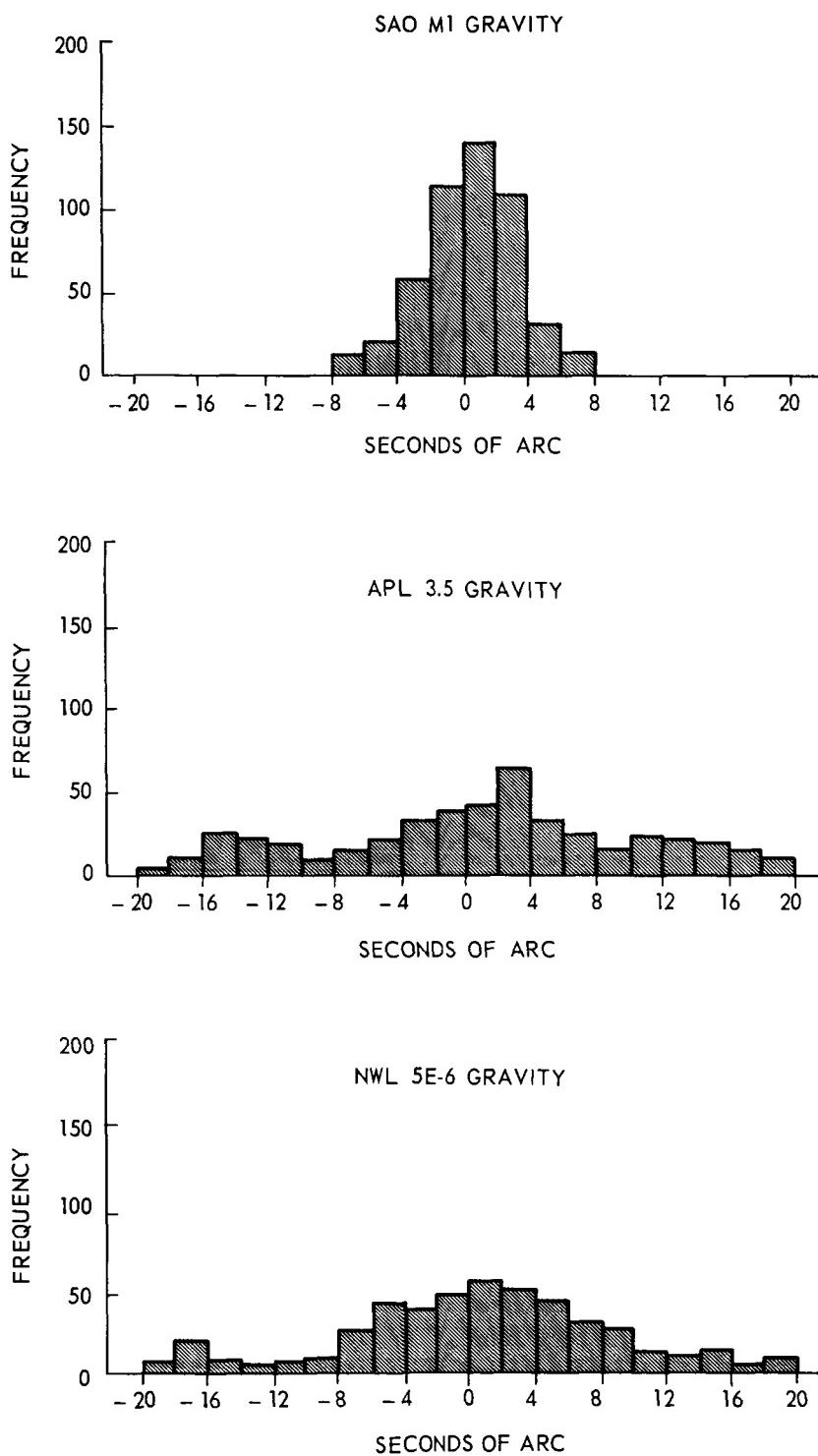


Figure 3. Right Ascension Residuals from 5 1/4 Day Arc

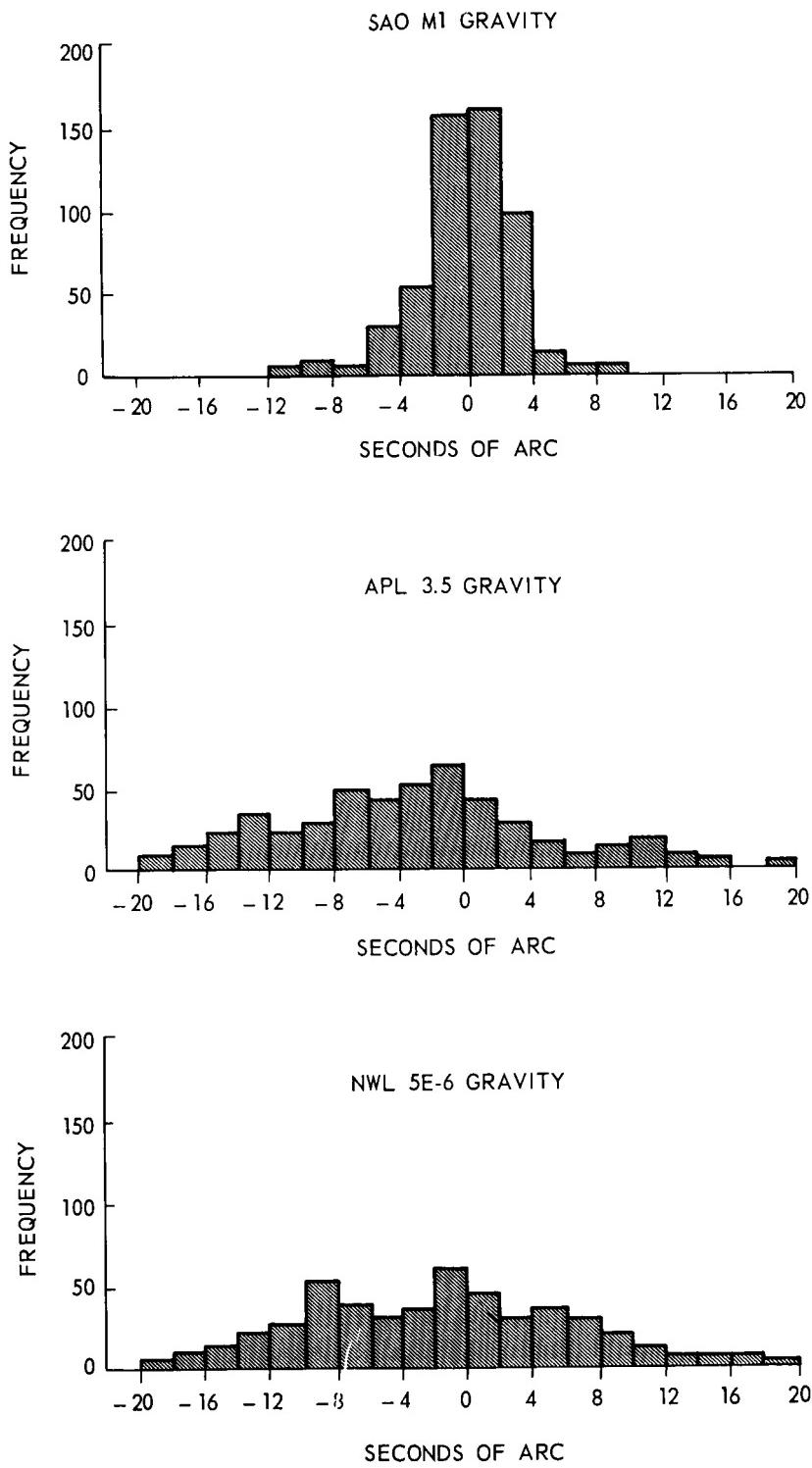


Figure 4. Declination Residuals from 5 1/4 Day Arc

Table IV  
Root Mean Squares About The Orbital Solution

| Arc Length | R.M.S. of Fit (Secs. of Arc) |         |          |
|------------|------------------------------|---------|----------|
|            | SAO M-1                      | APL 3.5 | NWL 5E-6 |
| 5-1/4 day  | 3.08                         | 11.14   | 11.01    |
| 1 day      | 2.33                         | 2.50    | 4.54     |

for the 5-1/4 day arc (Figures 3-4) where the distributions of the right ascension and declination residuals for the APL 3.5 and NWL 5E-6 solutions are obviously non normal.

#### 4.0 TRAJECTORY DIFFERENCES

Satellite position differences were computed at five minute intervals using the orbital solution obtained from the SAO M-1 coefficients as a standard for comparing the solutions obtained for the same data set when the APL 3.5 and NWL 5E-6 gravitational coefficients were used. These position differences were resolved into along track, cross track and radial components and are shown in Figures 5-8.

The along track differences were the largest. They were as large as 400 meters for the 5-1/4 day arc and 200 meters for the 1 day arc. The cross track and radial differences were approximately the same order of magnitude and were as large as 100 meters for the 5-1/4 day arc and 50 meters for the 1 day arc. The differences have a period approximately equal to the period of the satellite (2 hrs), and, in addition, the along track differences have some other long period associated with them. The periods of the along track, cross track, and radial differences are not in phase, and in general, the minima occur where there is good data coverage; this is shown by the solid blocks in the figures.

#### 5.0 EVALUATION OF THE ROSMAN GRARR RANGE ACCURACY

The range measurements of the Goddard Range and Range Rate (GRARR) S Band Tracking System at Rosman, North Carolina, were evaluated by comparing the actual measurements with values computed from the optical reference orbits (Reference 5). The 5-1/4 day arc and the 1 day arc discussed in Section 3.0 were

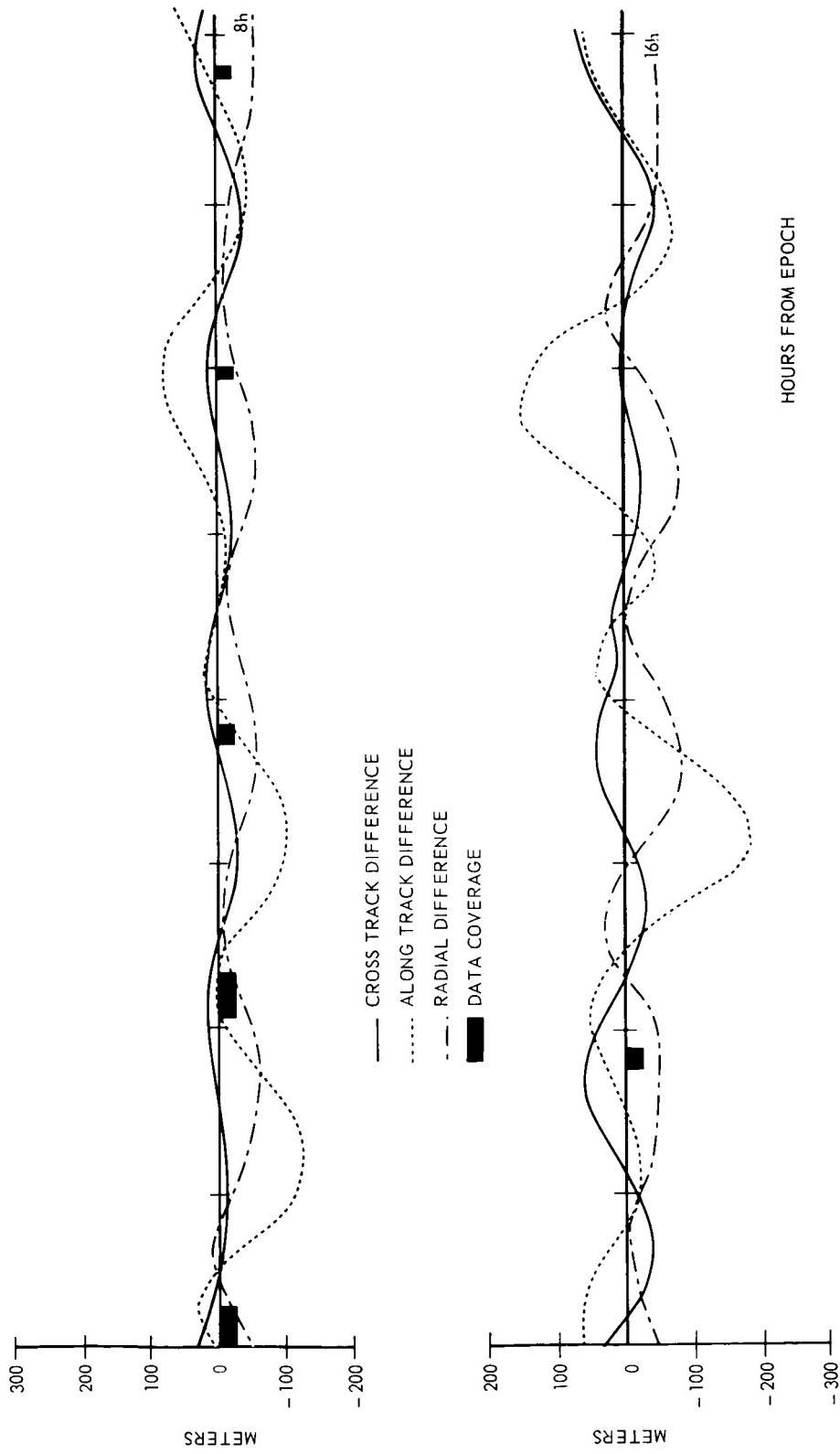


Figure 5. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 1 Day Arc

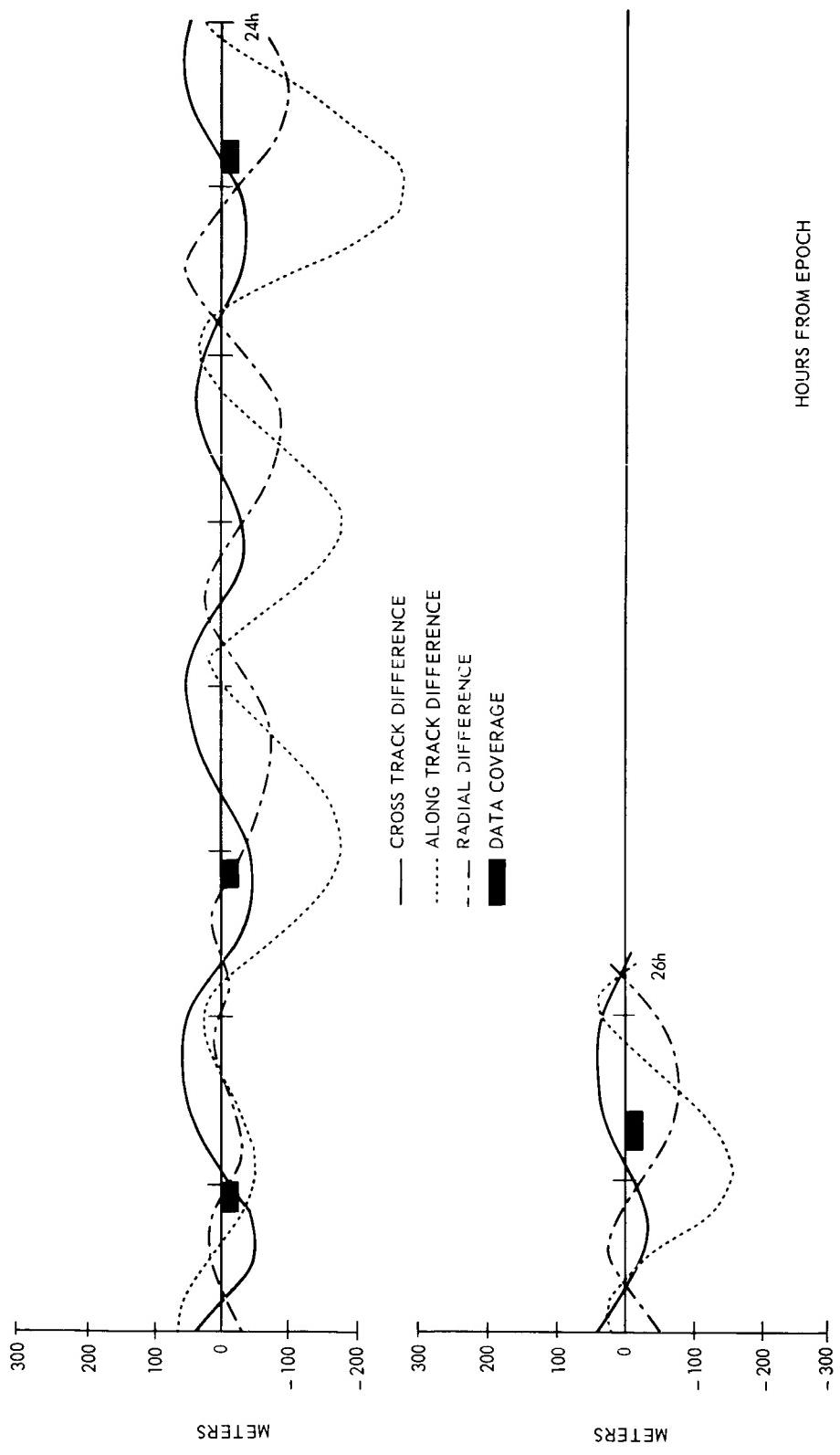


Figure 5. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 1 Day Arc (Continued)

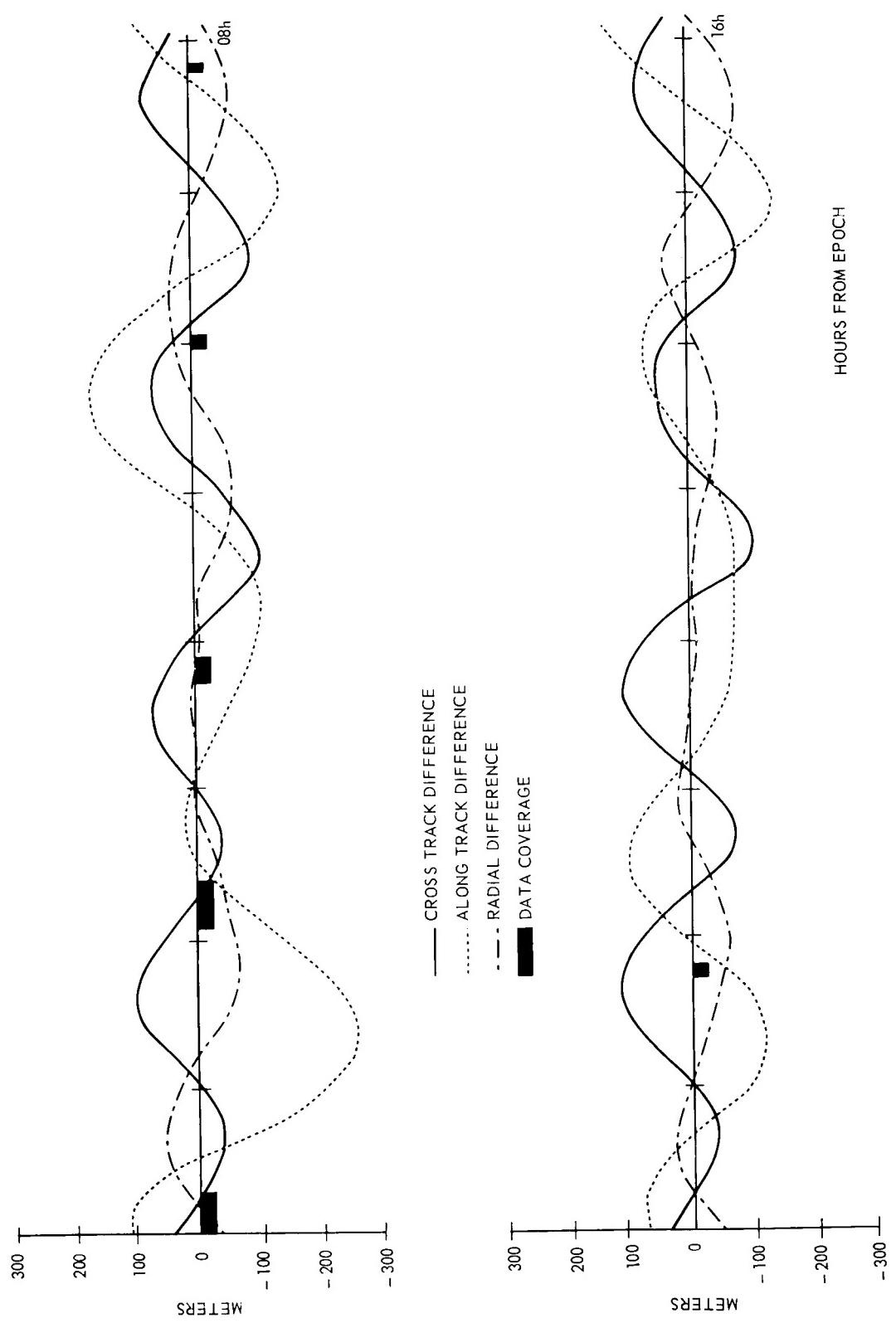


Figure 6. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 1 Day Arc

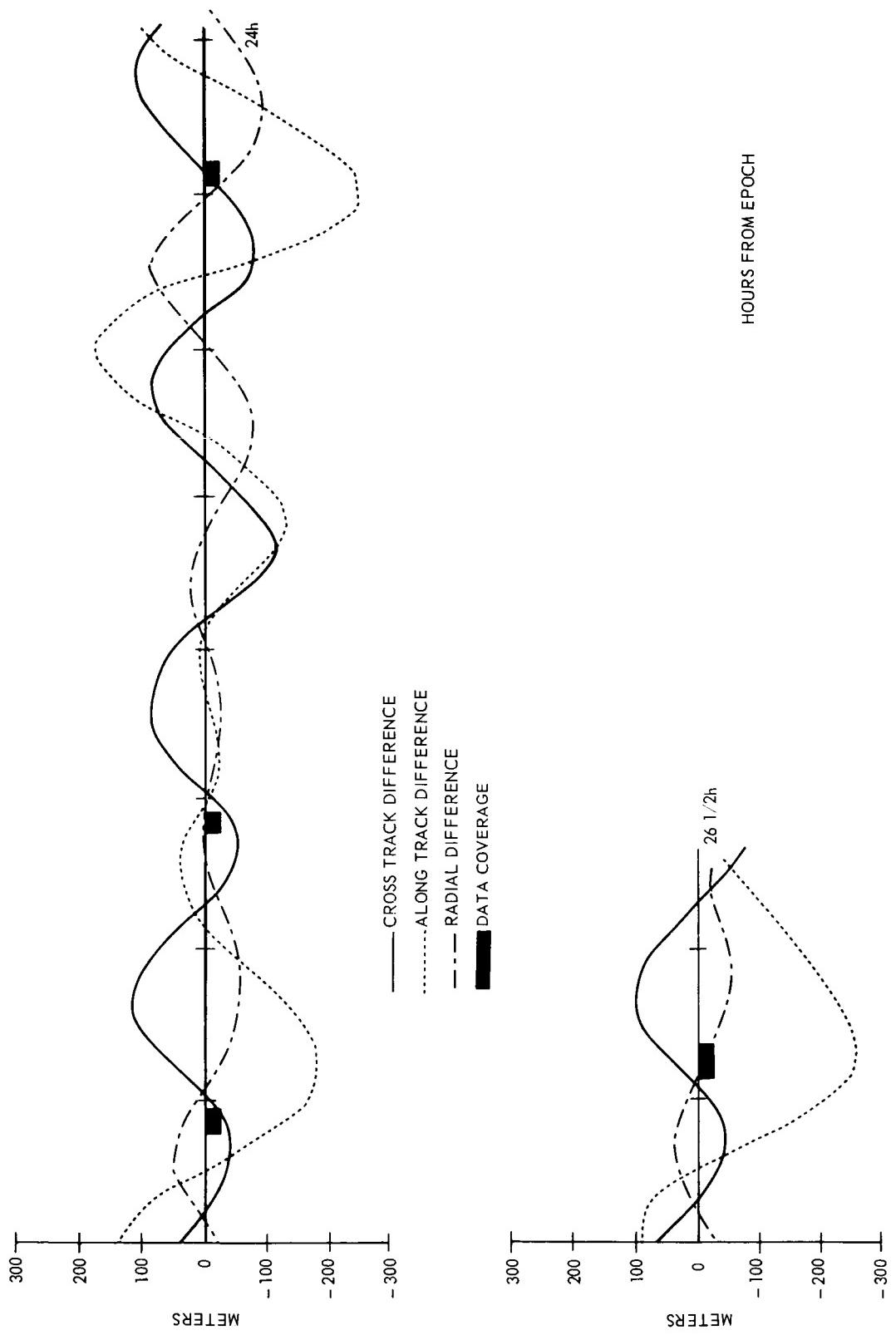


Figure 6. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models - 1 Day Arc (Continued)

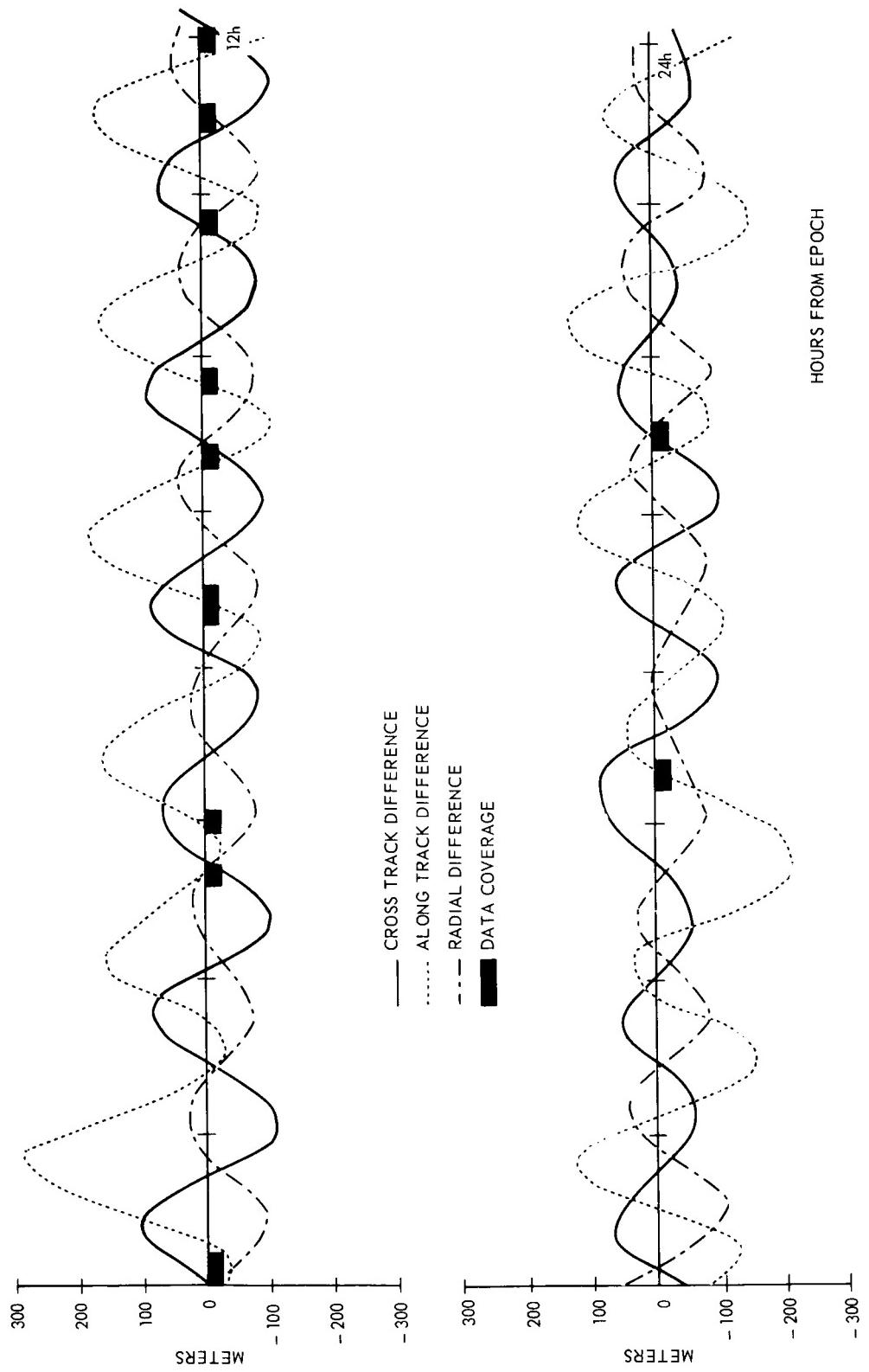
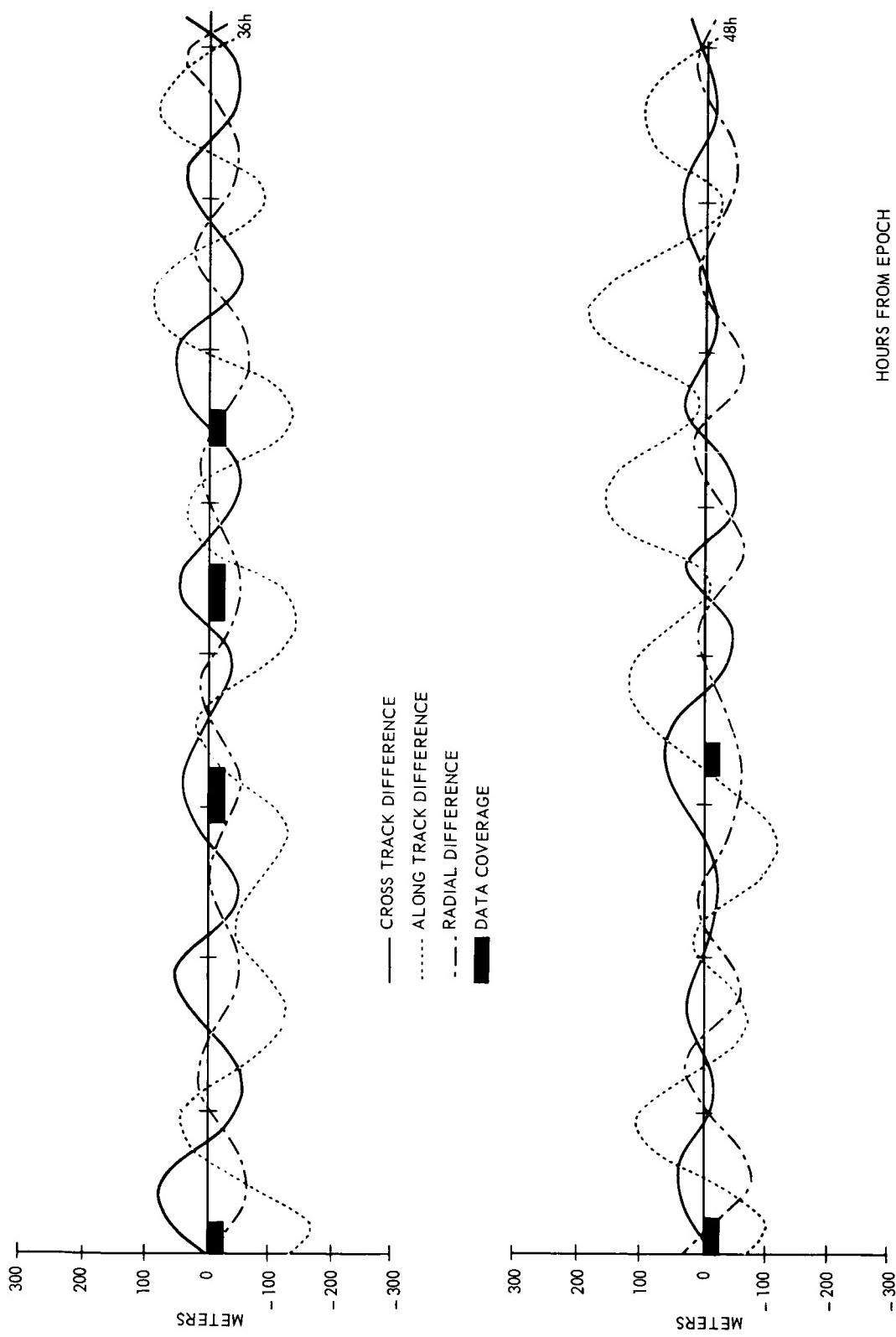


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc



**Figure 7.** Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc (Continued)

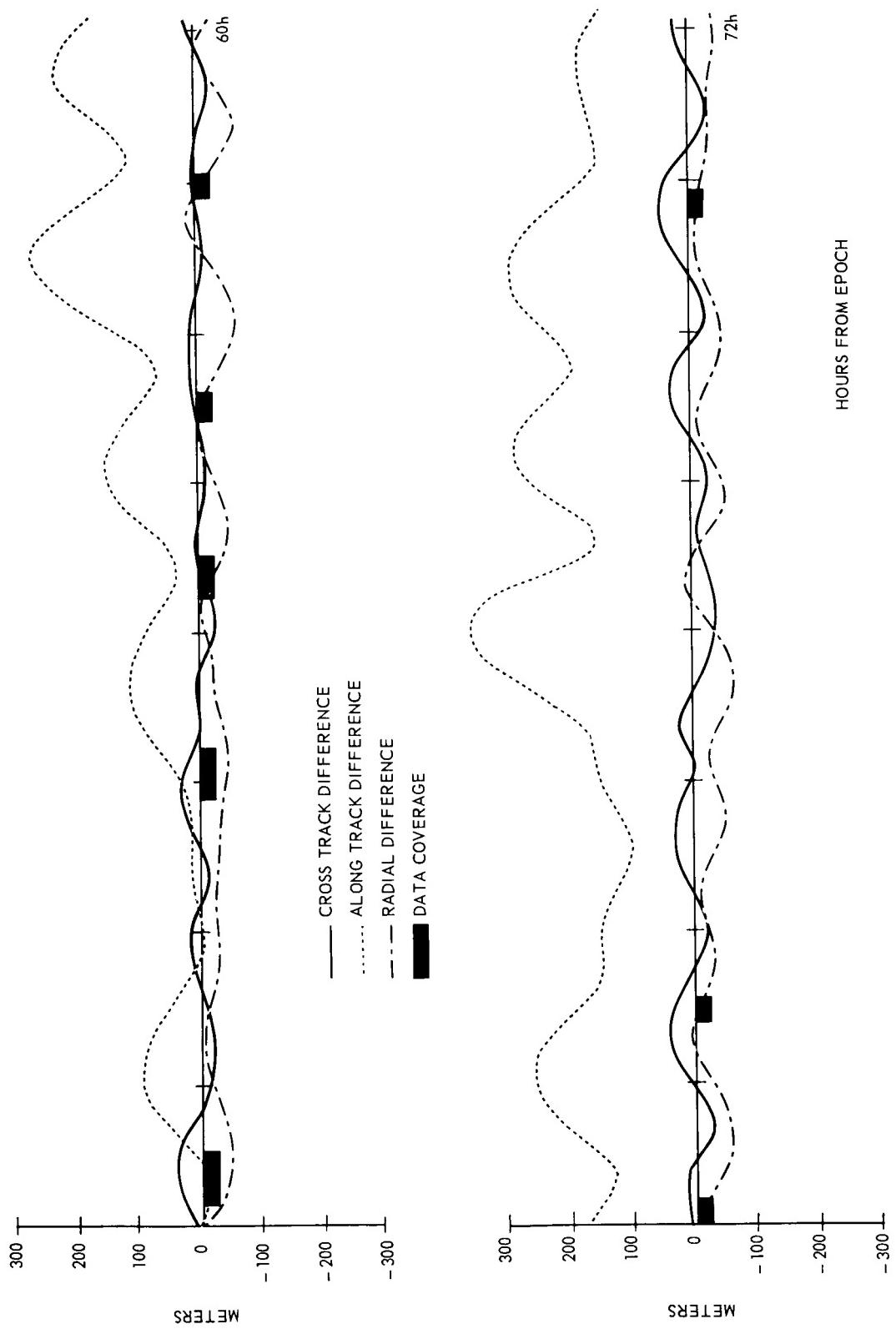


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc (Continued)

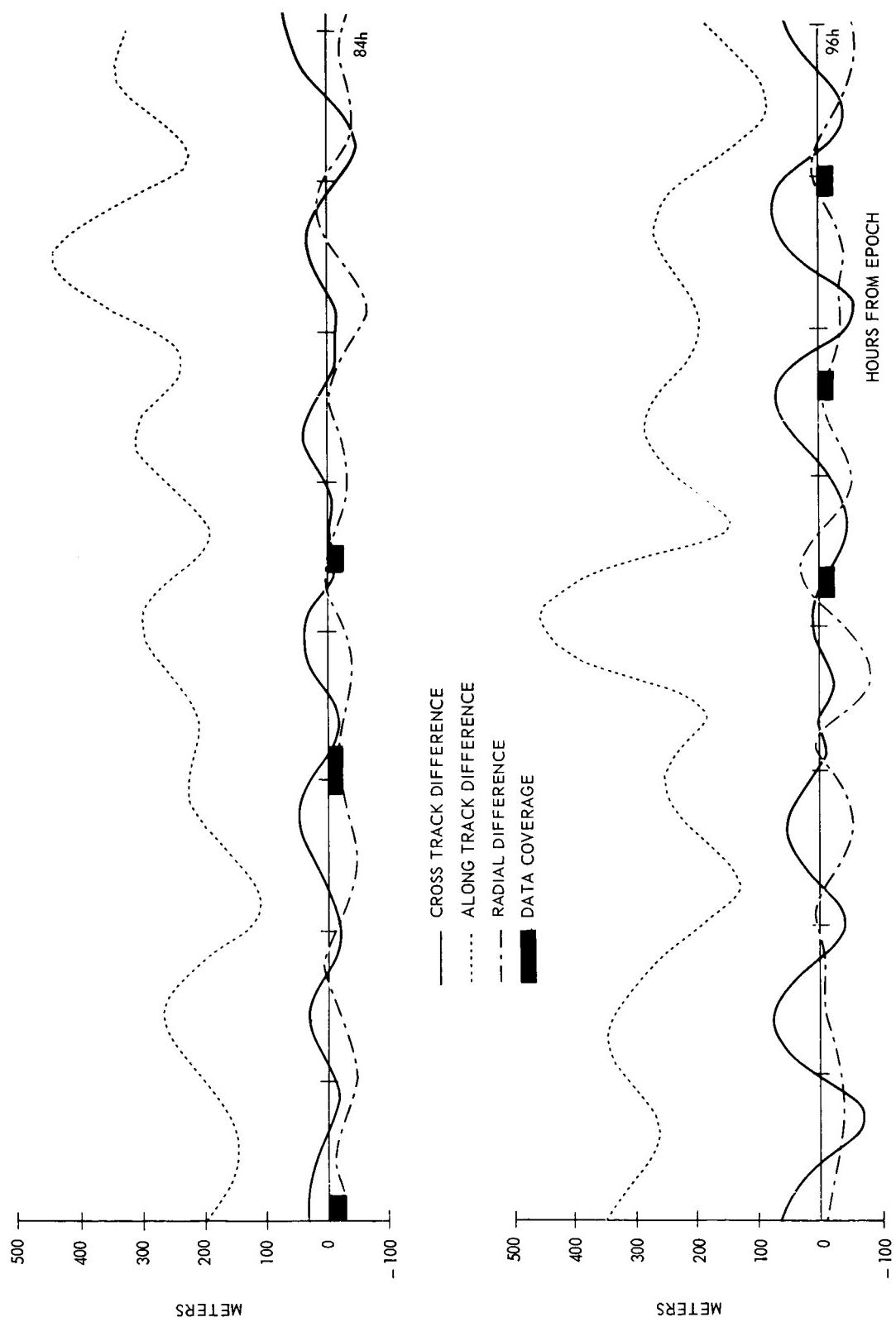


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models – 5 1/4 Day Arc (Continued)

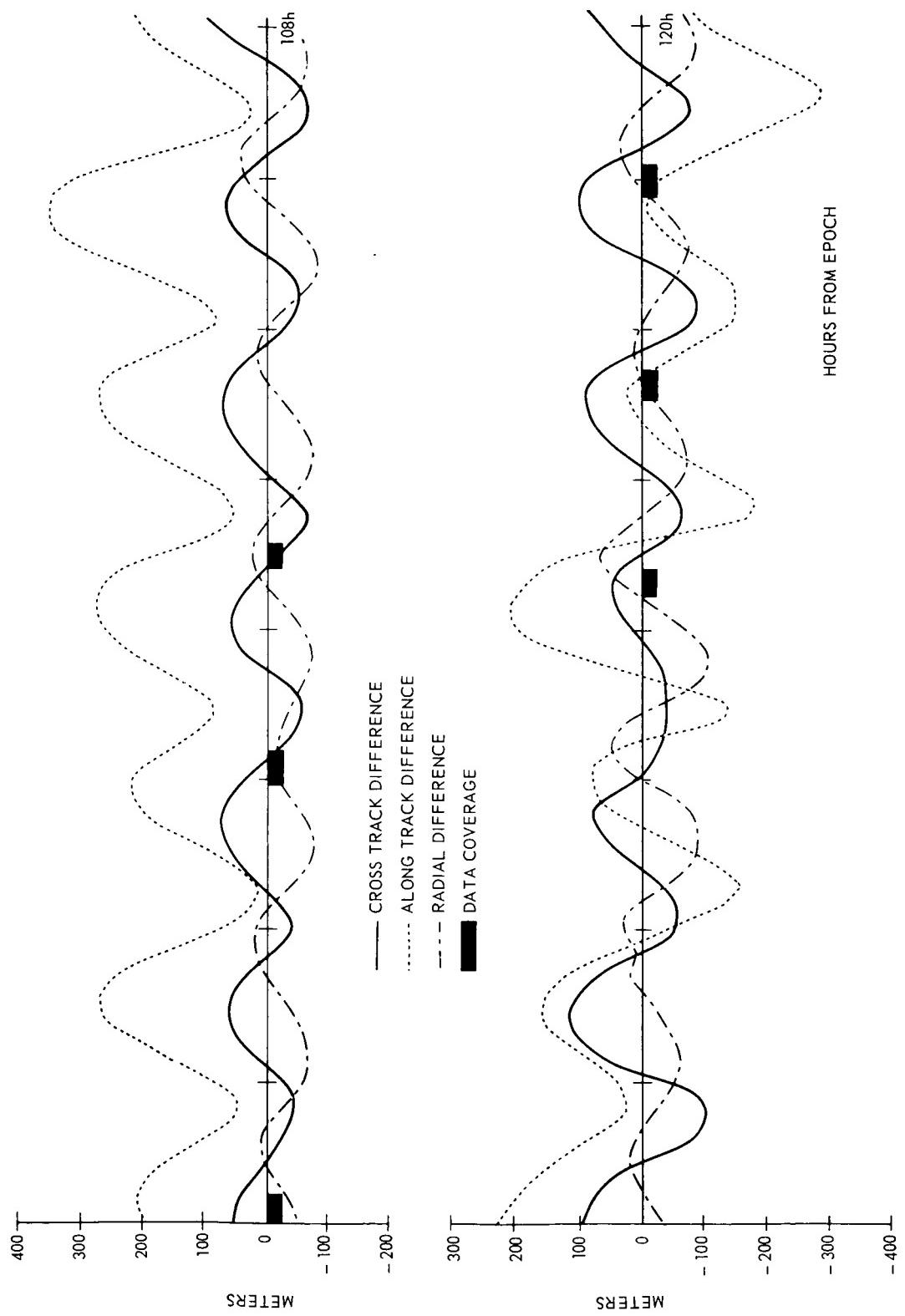


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models - 5 1/4 Day Arc (Continued)

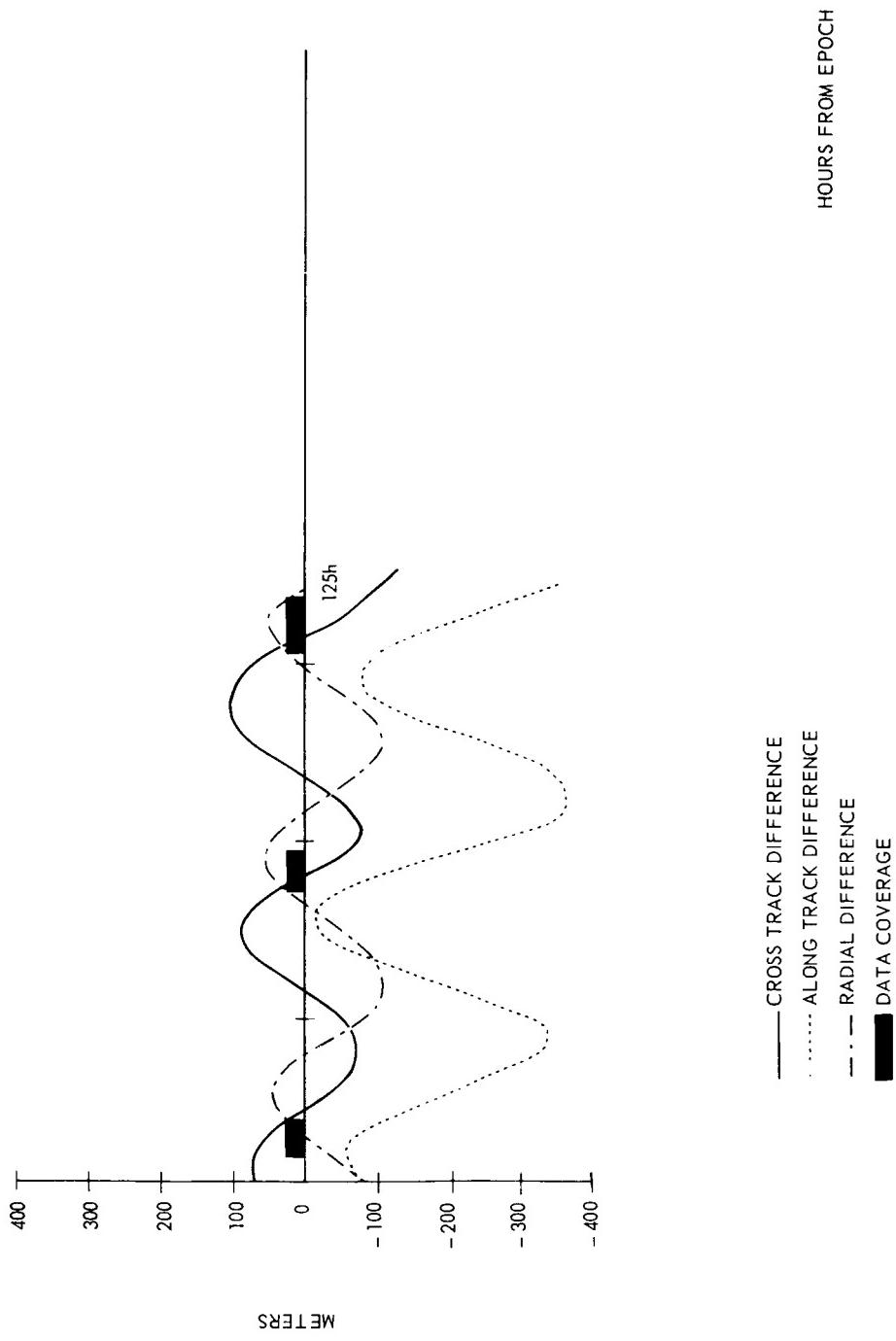


Figure 7. Differences Between Trajectories Obtained from SAO M-1 and APL 3.5 Gravity Models - 5 1/4 Day Arc (Continued)

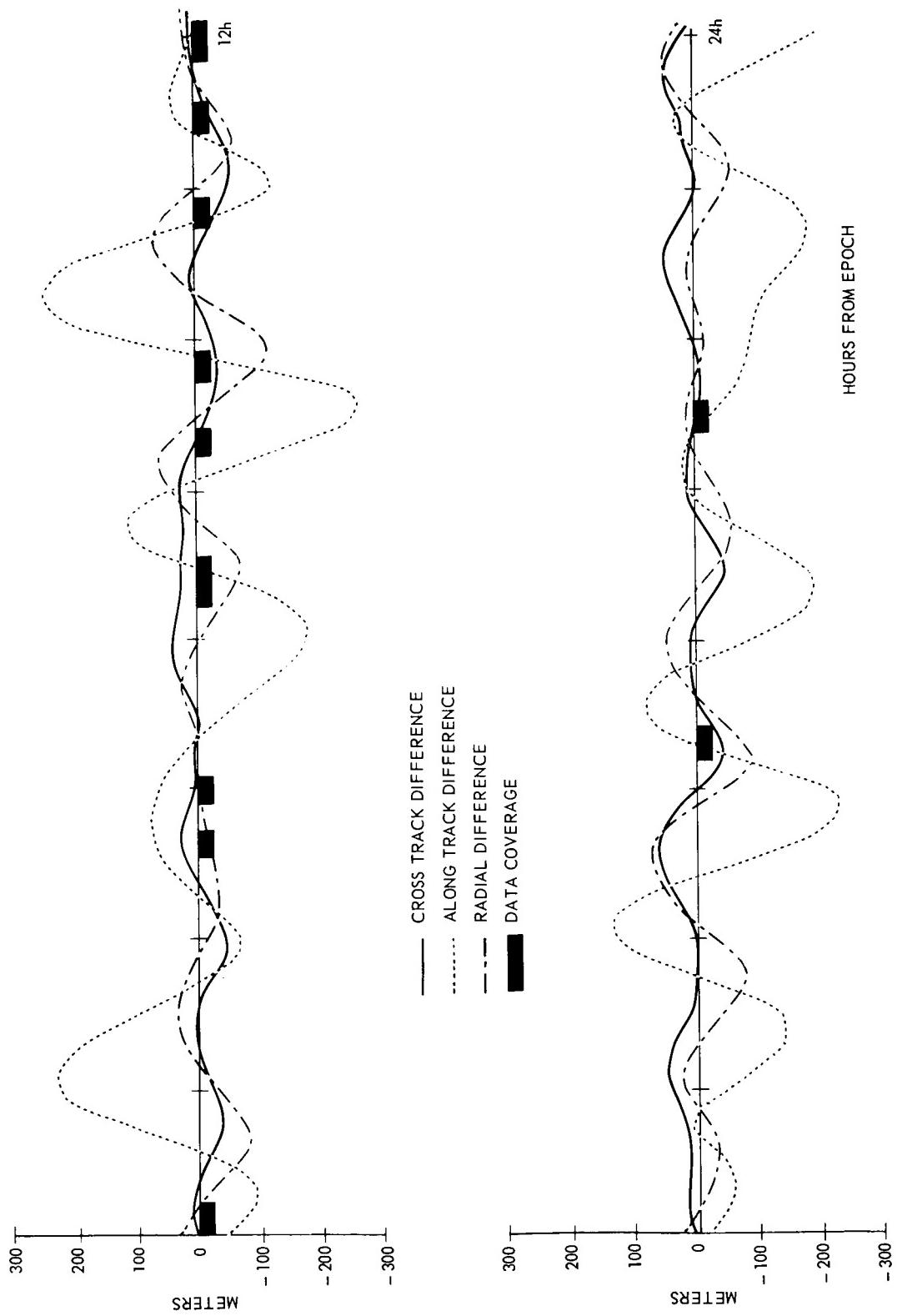


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc

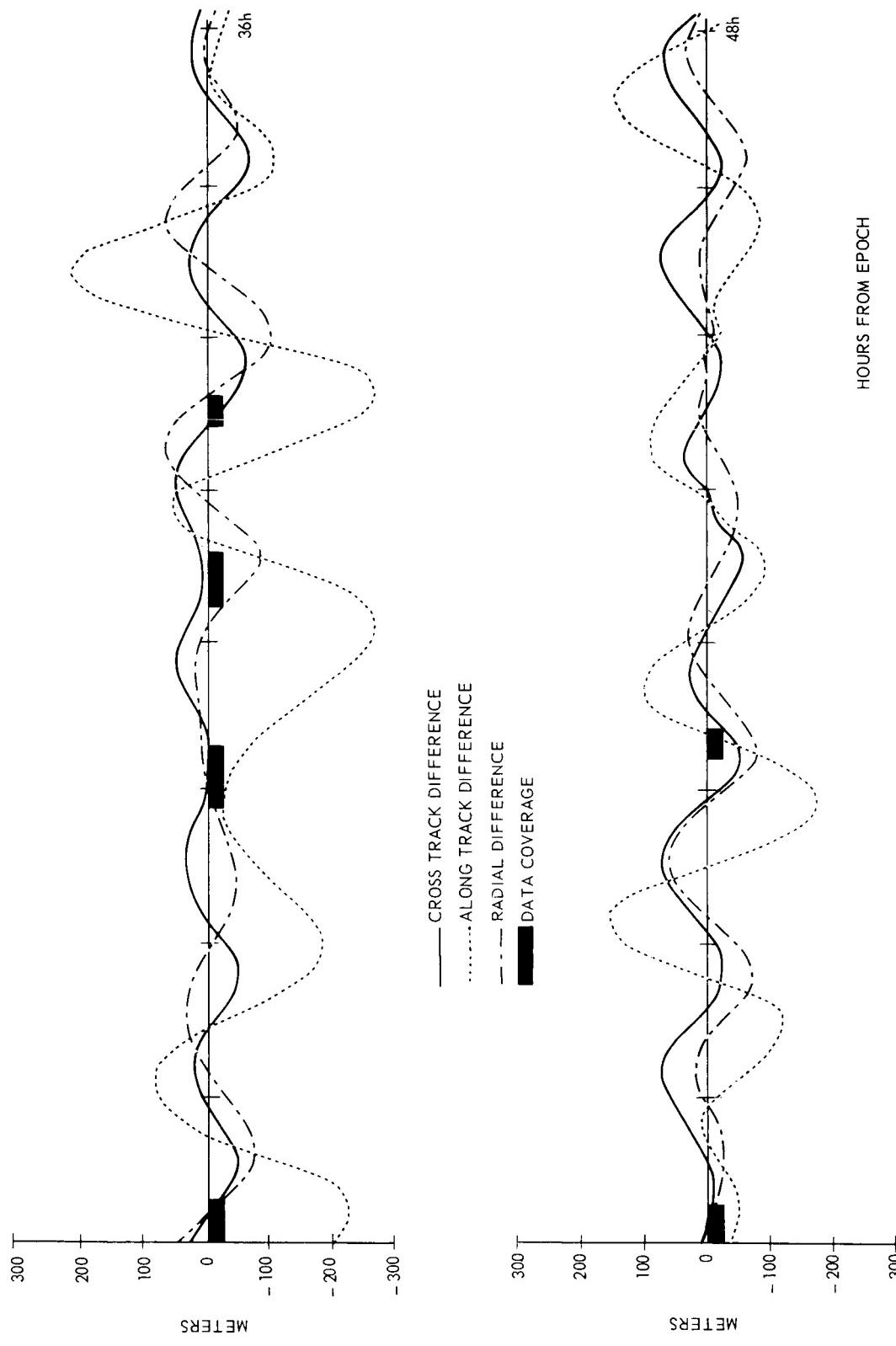


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc (Continued)

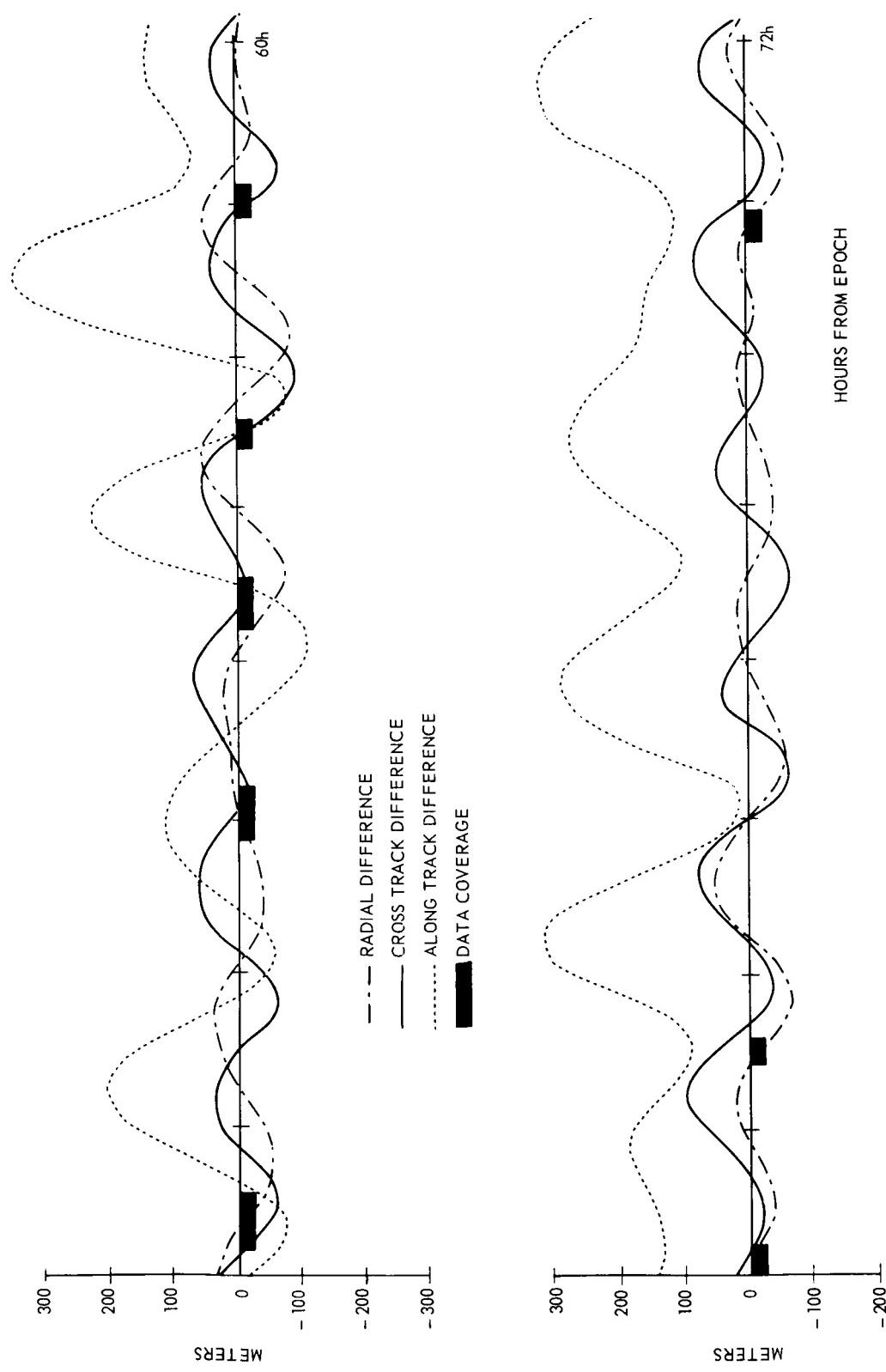


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models - 5 1/4 Day Arc (Continued)

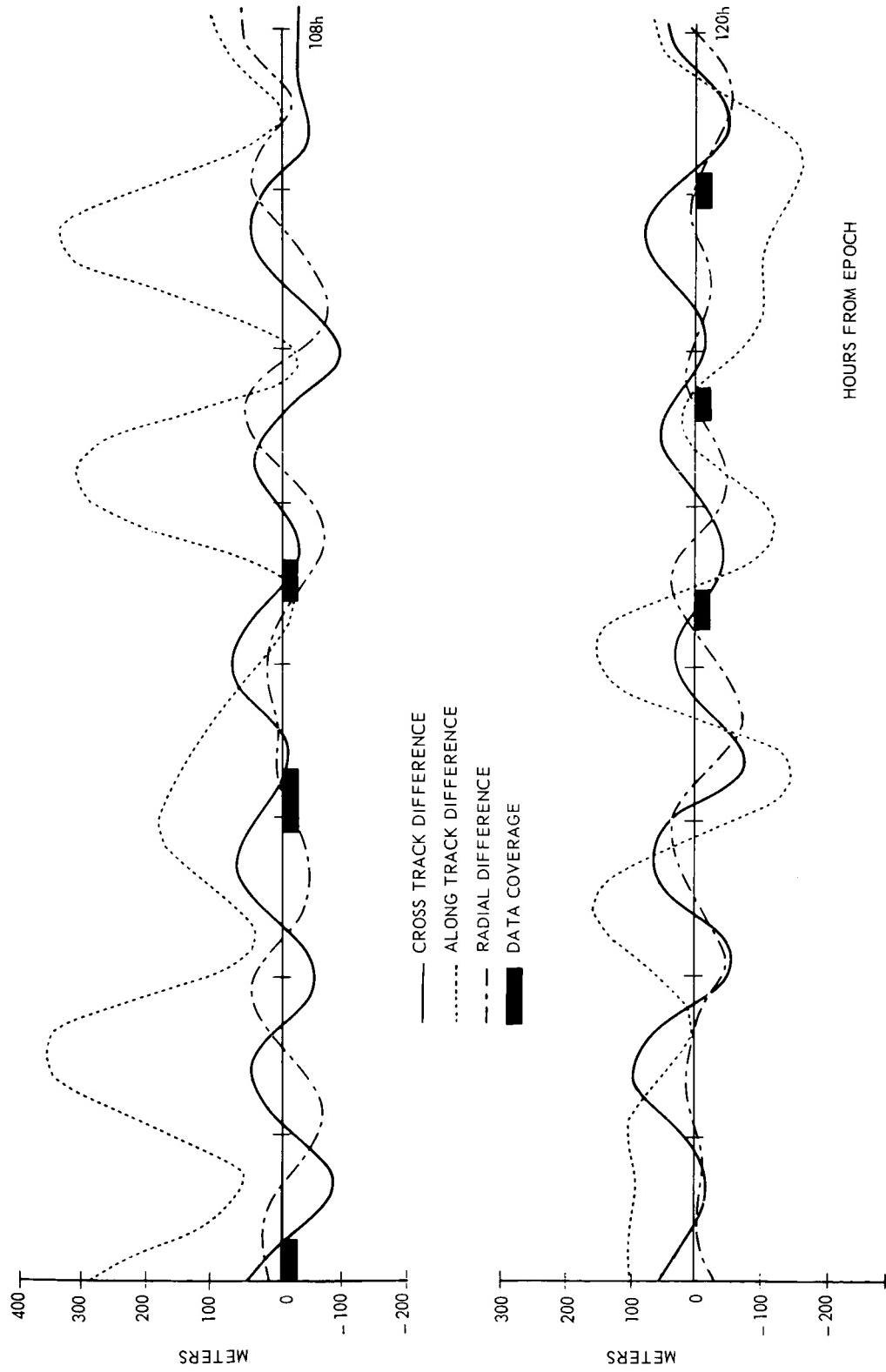


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models – 5 1/4 Day Arc (Continued)

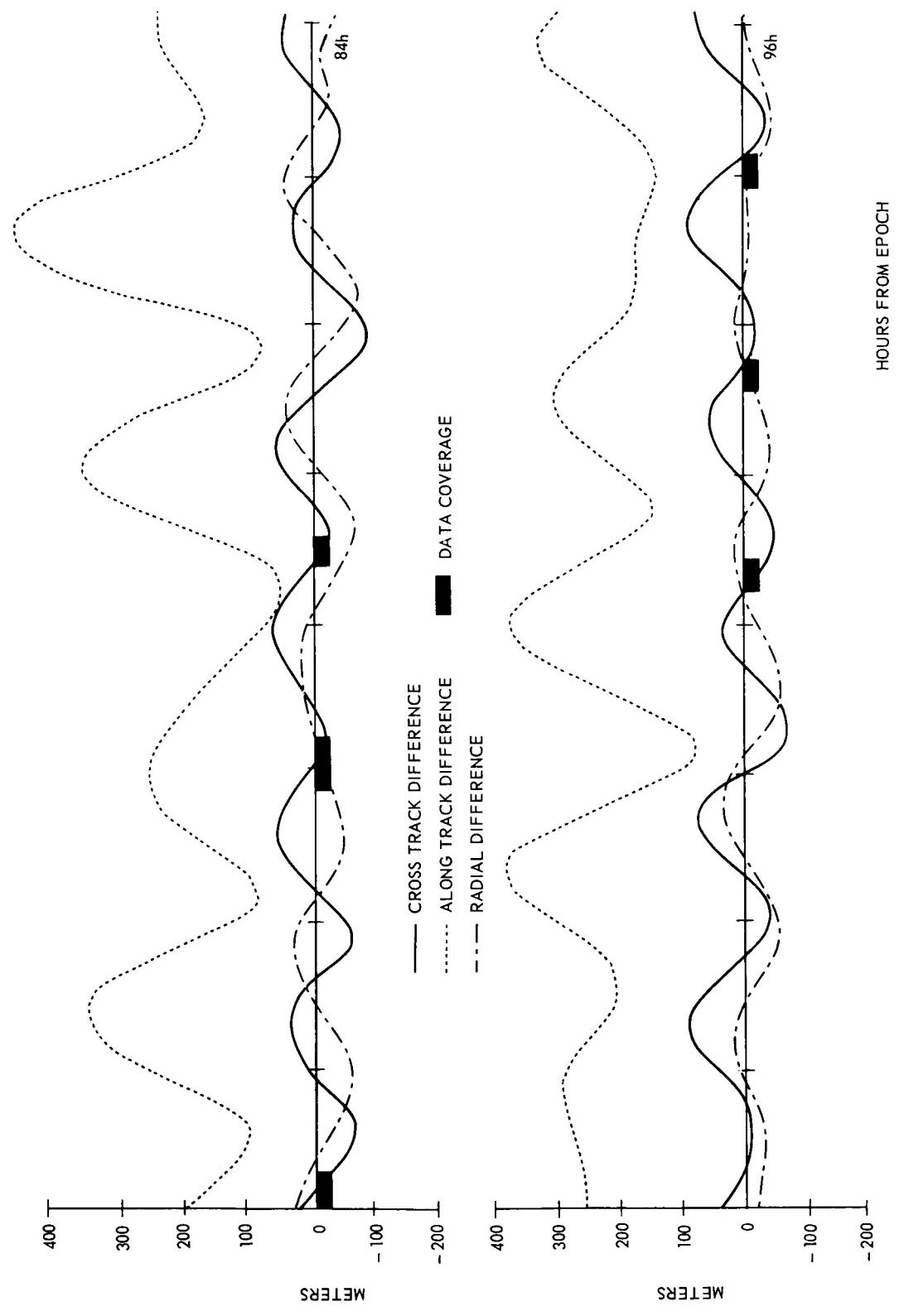


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models - 5 1/4 Day Arc (Continued)

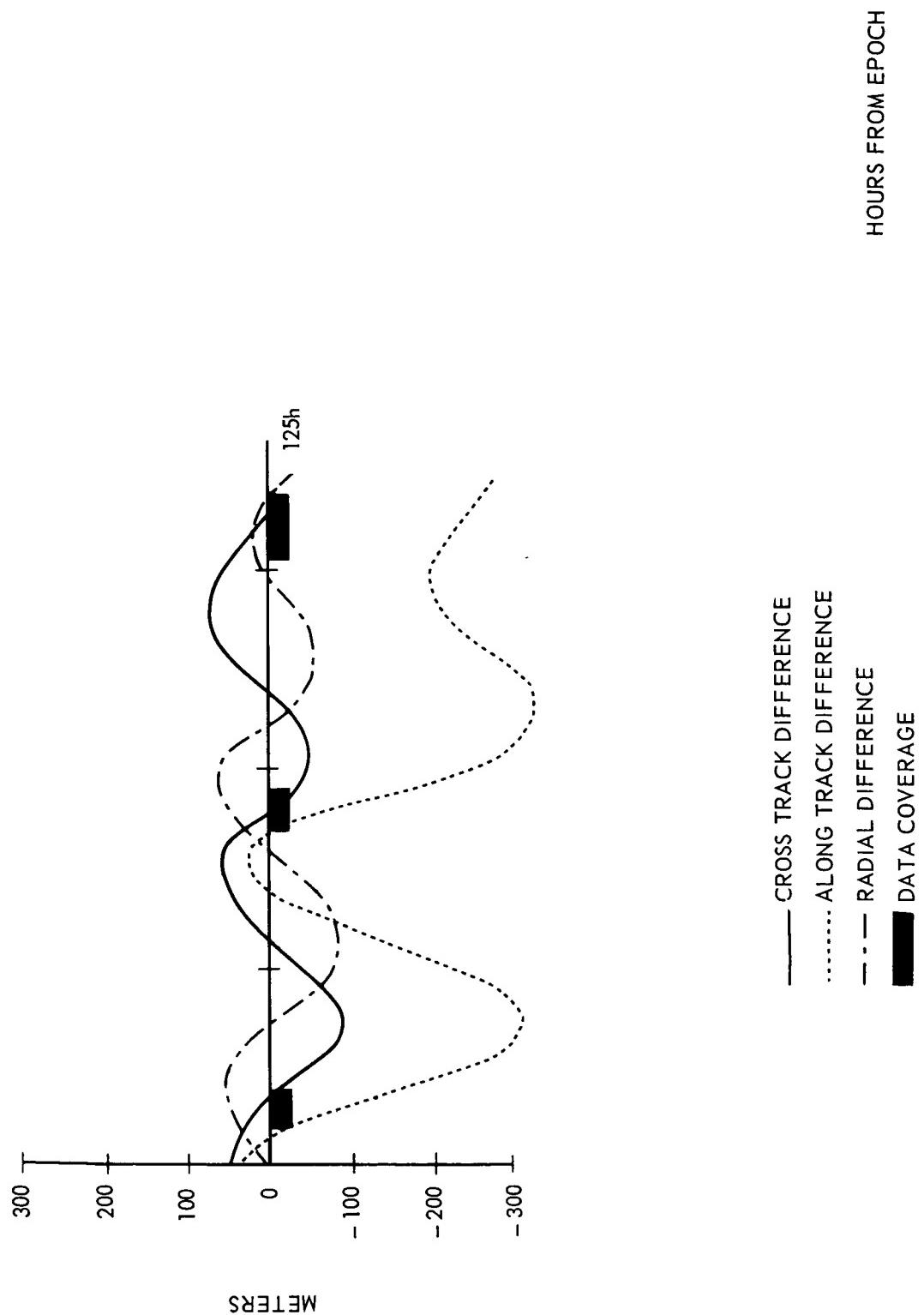


Figure 8. Differences Between Trajectories Obtained from SAO M-1 and NWL 5E-6 Gravity Models - 5 1/4 Day Arc (Continued)

used as the reference orbits. A summary of the station pass times, simultaneous optical coverage and maximum elevation angles for 15 GRARR passes recorded at Rosman during the 5-1/4 day optical arc is presented in Table V. It should be noted that a large percentage of the optical data used in the determination of the reference orbital solutions was recorded by tracking stations located on or near

Table V  
Summary of GRARR Passes At Rosman Occurring  
During The 5-1/4 Day Optical Orbital Arc

| Pass No. | Transponder Channel* | Date     | Time            | No. of Obs. in Pass |         | Max. Elevation Angle |
|----------|----------------------|----------|-----------------|---------------------|---------|----------------------|
|          |                      |          |                 | R/R                 | Optical |                      |
| 652      | A                    | 12/31/65 | 06 <sup>H</sup> | 18                  | 18      | 31.3°                |
| 653      | A                    | 12/31/65 | 08 <sup>H</sup> | 28                  | 30      | 65.4°                |
| 664      | A                    | 1/1/66   | 06 <sup>H</sup> | 28                  | 78      | 36.6°                |
| 665      | A                    | 1/1/66   | 08 <sup>H</sup> | 32                  | 95      | 51.8°                |
| 673      | A                    | 1/1/66   | 23 <sup>H</sup> | 34                  | 0       | 53.5°                |
| 676      | A                    | 1/2/66   | 06 <sup>H</sup> | 32                  | 106     | 43.3°                |
| 677      | A                    | 1/2/66   | 08 <sup>H</sup> | 28                  | 138     | 40.2°                |
| 685      | A                    | 1/2/66   | 23 <sup>H</sup> | 34                  | 10      | 46.5°                |
| 688      | A                    | 1/3/66   | 06 <sup>H</sup> | 30                  | 101     | 52.2°                |
| 689      | A                    | 1/3/66   | 08 <sup>H</sup> | 14                  | 79      | 30.1°                |
| 697      | A                    | 1/3/66   | 23 <sup>H</sup> | 44                  | 0       | 40.8°                |
| 700      | C                    | 1/4/66   | 06 <sup>H</sup> | 36                  | 100     | 62.7°                |
| 708      | C                    | 1/4/66   | 21 <sup>H</sup> | 48                  | 0       | 84.2°                |
| 709      | C                    | 1/4/66   | 23 <sup>H</sup> | 42                  | 14      | 35.8°                |
| 712      | A                    | 1/5/66   | 06 <sup>H</sup> | 36                  | 66      | 76.6°                |

\*The GEOS-I GRARR transponder contained two channels denoted A and C which received signals at 2271.9328 MHz and 2270.1328 MHz respectively.

the North American Continent (Table III) and also most of the Rosman GRARR passes had simultaneous optical data coverage.

For each GRARR pass over Rosman, zero set range bias errors, timing errors, and random errors were estimated from the residual differences between the observed and calculated ranges; these are summarized in Tables VI-VIII. The 12 A channel passes had a mean zero set error of -10 meters with a standard deviation of 8.8 meters, and a timing error of -2.4 milliseconds with a standard deviation of 2.4 milliseconds when compared with the orbital solution determined with the SAO M-1 gravitational coefficients; a mean zero set error of -33.7 meters with a standard deviation of 21.0 meters, and a timing error of -0.8 milliseconds with a standard deviation of 9.8 milliseconds when compared with the orbital solution determined with the NWL 5E-6 coefficients; and a mean zero set error of -34.6 meters with a standard deviation of 30.7 meters, and a timing error of 3.1 milliseconds with a standard deviation of 22.1 milliseconds when compared with orbital solution determined with the APL 3.5 coefficients. As indicated by the standard deviations associated with these errors, the estimates obtained from the orbital solutions fitted using the SAO M-1 set of coefficients were significantly less variable than those obtained using the other two sets. In addition, the estimates obtained from the shorter overlapping 1 day arc were only consistent with the 5-1/4 day arc estimates when the orbital solutions were obtained with the SAO M-1 set of coefficients.

## 6.0 ESTIMATION OF COORDINATES FOR THE GRARR MADGAR SITE

Two independent estimates of the coordinates of the GRARR site in Tananarive, Madagascar (MADGAR) were obtained using each set of coefficients (Reference 6). One estimate was obtained from optical flash sequence data recorded by the MOTS 40" camera (1 TANAN) during July 1966 and the other from range measurements taken at MADGAR during November 1965. The data sets used for these estimations are shown in Tables IX and X.

The two sets of coordinates estimated using the SAO M-1 coefficients were very consistent, within 5 meters of each other; whereas the estimates obtained using the other two sets of coefficients were not at all consistent. These estimates are shown in Table XI and Figure 9.

Table VI  
 Summary of Rosman Zero-Set Range Bias Error Estimates  
 (meters)

| Pass No.  | Transponder Channel | SAO    |       | M1    | NWL    |       | 5E-6 | APL   |       | 3.5 |
|-----------|---------------------|--------|-------|-------|--------|-------|------|-------|-------|-----|
|           |                     | No. 1* | No. 2 |       | No. 1  | No. 2 |      | No. 1 | No. 2 |     |
| 652       | A                   | -16.5  |       |       | -26.5  |       |      | -98.8 |       |     |
| 653       | A                   | - 6.1  |       |       | -45.9  |       |      | -35.9 |       |     |
| 664       | A                   | - 5.0  |       |       | -18.0  |       |      | -74.1 |       |     |
| 665       | A                   | - 2.0  |       |       | -39.4  |       |      | -16.3 |       |     |
| 673       | A                   | -19.1  |       |       | -44.7  |       |      | -15.8 |       |     |
| 676       | A                   | 2.3    | 4.2   | 8.1   | 6.6    | -25.8 |      | -24.6 |       |     |
| 677       | A                   | 0.2    | 7.4   | -51.8 | - 23.6 | -20.2 |      | 3.8   |       |     |
| 685       | A                   | -29.5  | -20.7 | -60.0 | -112.5 | -46.7 |      | -79.0 |       |     |
| 688       | A                   | - 3.3  | - 1.0 | 8.4   | - 7.9  | - 2.2 |      | - 1.7 |       |     |
| 689       | A                   | -14.9  | - 7.7 | -71.2 | - 35.8 | -38.7 |      | - 7.7 |       |     |
| 697       | A                   | -16.0  |       | -49.4 |        | -52.8 |      |       |       |     |
| 700       | C                   | 20.6   |       | 25.4  |        | 36.5  |      |       |       |     |
| 708       | C                   | 16.8   |       | 10.5  |        | 7.9   |      |       |       |     |
| 709       | C                   | 17.0   |       | -17.7 |        | -33.7 |      |       |       |     |
| 712       | A                   | - 9.5  |       | -14.5 |        | 11.8  |      |       |       |     |
| Mean      | A                   | -10.0  |       | -33.7 |        | -34.6 |      |       |       |     |
| Std. dev. | A                   | 8.8    |       | 21.0  |        | 30.7  |      |       |       |     |
| Mean      | C                   | 18.1   |       | 6.1   |        | 3.6   |      |       |       |     |

\*No. 1 and No. 2 refer to the  $5\frac{1}{4}$  day and 1 day orbital arcs described in Section 3.0.

Table VII  
Summary of Rosman Timing Error Estimates  
(milliseconds)

| Pass No.  | Transponder Channel | SAO   |       | M1    |       | NWL   |       | 5E-6  |       | APL   |       | 3.5   |       |
|-----------|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|           |                     | No. 1 | No. 2 |
| 652       | A                   | -2.0  |       |       |       | 6.1   |       |       |       | - 7.7 |       |       |       |
| 653       | A                   | 1.5   |       |       |       | -11.1 |       |       |       | - 4.3 |       |       |       |
| 664       | A                   | -3.9  |       |       |       | - 9.9 |       |       |       | -22.7 |       |       |       |
| 665       | A                   | 1.0   |       |       |       | -23.7 |       |       |       | -16.9 |       |       |       |
| 673       | A                   | -3.4  |       |       |       | -17.4 |       |       |       | - 6.5 |       |       |       |
| 676       | A                   | -6.3  | -6.9  |       |       | 10.0  |       | 12.9  |       | - 0.9 |       | -1.2  |       |
| 677       | A                   | -0.2  | -0.3  |       |       | - 5.0 |       | - 7.3 |       | 3.4   |       | 0.1   |       |
| 685       | A                   | -3.5  | -0.6  |       |       | 14.2  |       | -12.2 |       | 31.3  |       | 1.5   |       |
| 688       | A                   | -5.0  | -5.3  |       |       | 31.4  |       | 10.7  |       | 25.1  |       | 0.7   |       |
| 689       | A                   | 0.1   | 1.2   |       |       | 13.2  |       | 12.5  |       | 25.6  |       | -1.5  |       |
| 697       | A                   | -3.0  |       |       |       | 19.6  |       |       |       | 38.9  |       |       |       |
| 700       | C                   | -5.4  |       |       |       | 18.1  |       |       |       | 18.9  |       |       |       |
| 708       | C                   | -2.3  |       |       |       | 3.3   |       |       |       | 2.7   |       |       |       |
| 709       | C                   | 3.4   |       |       |       | -18.9 |       |       |       | 5.5   |       |       |       |
| 712       | A                   | -2.8  |       |       |       | -36.4 |       |       |       | -28.2 |       |       |       |
| Mean      | A                   | -2.4  |       |       |       | - 0.8 |       |       |       | 3.1   |       |       |       |
| Std. dev. | A                   | 2.4   |       |       |       | 9.8   |       |       |       | 22.1  |       |       |       |
| Mean      | C                   | -1.4  |       |       |       | 0.8   |       |       |       | 9.0   |       |       |       |

Table VIII  
 Summary of Random Error Estimates  
 (meters)

| Pass No. | Transponder Channel | SAO M1 |       | NWL 5E-6 |       | APL 3.5 |       |
|----------|---------------------|--------|-------|----------|-------|---------|-------|
|          |                     | No. 1  | No. 2 | No. 1    | No. 2 | No. 1   | No. 2 |
| 652      | A                   | 3.3    |       | 3.5      |       | 6.0     |       |
| 653      | A                   | 3.6    |       | 10.5     |       | 7.3     |       |
| 664      | A                   | 3.2    |       | 3.6      |       | 6.1     |       |
| 665      | A                   | 4.5    |       | 12.0     |       | 3.6     |       |
| 673      | A                   | 2.6    |       | 4.7      |       | 3.1     |       |
| 676      | A                   | 2.9    | 3.0   | 3.9      | 5.3   | 5.0     | 3.8   |
| 677      | A                   | 3.2    | 4.0   | 10.4     | 4.7   | 2.8     | 5.3   |
| 685      | A                   | 2.5    | 2.3   | 3.5      | 10.5  | 2.6     | 5.2   |
| 688      | A                   | 4.5    | 5.0   | 8.3      | 10.3  | 7.0     | 8.2   |
| 689      | A                   | 4.1    | 3.8   | 7.4      | 5.0   | 3.9     | 3.9   |
| 697      | A                   | 3.4    |       | 3.5      |       | 3.8     |       |
| 700      | C                   | 5.8    |       | 10.8     |       | 16.8    |       |
| 708      | C                   | 4.5    |       | 3.9      |       | 5.3     |       |
| 709      | C                   | 3.1    |       | 4.4      |       | 3.6     |       |
| 712      | A                   | 6.0    |       | 8.0      |       | 22.7    |       |
| Mean     | A                   | 3.7    |       | 6.6      |       | 6.2     |       |
| Mean     | C                   | 4.5    |       | 6.4      |       | 8.6     |       |

Table IX  
 Summary of Optical Data by Station  
 For July 9, 10, and 11, 1966

| Station | No. of Measurements |             |
|---------|---------------------|-------------|
|         | Right Ascension     | Declination |
| 1TANAN  | 14                  | 14          |
| 1ROSMA  | 7                   | 7           |
| 1COLBA  | 14                  | 14          |
| 1BPOIN  | 14                  | 14          |
| 1DENVR  | 20                  | 20          |
| 1JOBUR  | 14                  | 14          |
| 1ORGAN  | 91                  | 91          |
| 1OLFAN  | 28                  | 28          |
| 1SPAIN  | 21                  | 21          |
| 1QUIPA  | 28                  | 28          |
| 1CURAC  | 28                  | 28          |
| 1JUPTR  | 35                  | 35          |
| 1VILDO  | 7                   | 7           |
| AUSBAK  | 14                  | 14          |
| 1MAUIO  | 28                  | 28          |
| EDWAFB  | 2                   | 2           |
| Total   | 365                 | 365         |

Table X  
 Summary of Optical and GRARR Data By Station  
 For November 28 and 29, 1965

| Station | No. of Measurements |             |
|---------|---------------------|-------------|
|         | Right Ascension     | Declination |
| 1ORGAN  | 59                  | 59          |
| 1OLFAN  | 1                   | 1           |
| 1SPAIN  | 1                   | 1           |
| 1QUIPA  | 2                   | 2           |
| 1CURAC  | 96                  | 96          |
| 1JUPTR  | 127                 | 127         |
| 1VILDO  | 1                   | 1           |
| Total   | 287                 | 287         |
|         | Range               |             |
| MADGAR  | 24                  |             |

Table XI  
Estimated Coordinates for Madgar

SAO M1 Gravity Model

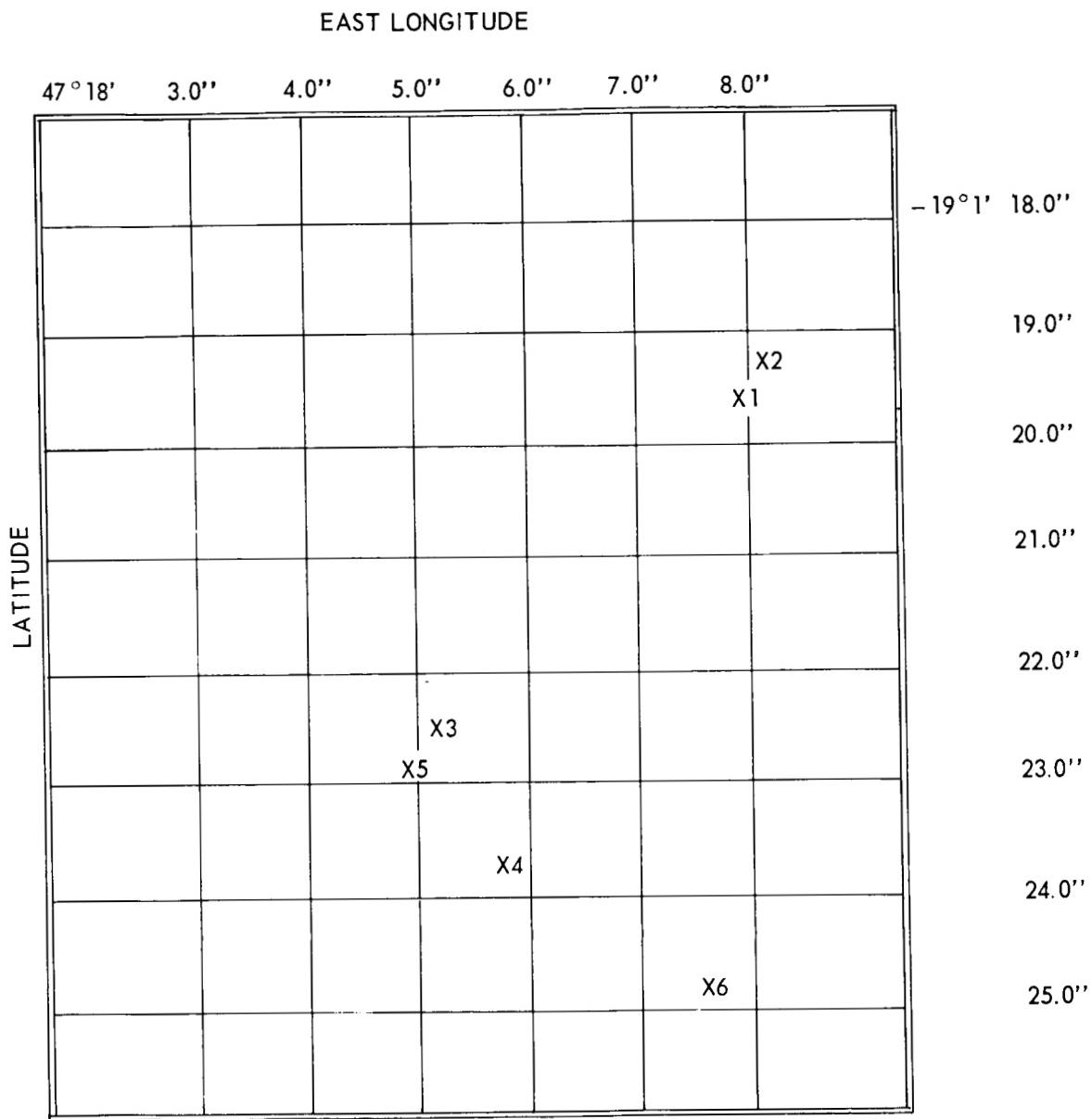
|                  | <u>Latitude</u> | <u>E. Longitude</u> | <u>Spheroid Height</u> |
|------------------|-----------------|---------------------|------------------------|
| Optical Estimate | -19° 1' 19.5"   | 47° 18' 7.9"        | 1380.0 meters          |
| GRARR Estimate   | -19° 1' 19.4"   | 47° 18' 8.0"        | 1382.6 meters          |
| Difference       | 0.1"            | -0.1"               | -2.6 meters            |

APL 3.5 Gravity Model

|                  | <u>Latitude</u> | <u>E. Longitude</u> | <u>Spheroid Height</u> |
|------------------|-----------------|---------------------|------------------------|
| Optical Estimate | -19° 1' 22.6"   | 47° 18' 5.1"        | 1454.5 meters          |
| GRARR Estimate   | -19° 1' 23.7"   | 47° 18' 5.7"        | 1443.1 meters          |
| Difference       | -1.1"           | -0.6"               | 11.4 meters            |

NWL 5E-6 Gravity Model

|                  | <u>Latitude</u> | <u>E. Longitude</u> | <u>Spheroid Height</u> |
|------------------|-----------------|---------------------|------------------------|
| Optical Estimate | -19° 1' 22.9"   | 47° 18' 4.8"        | 1458.0 meters          |
| GRARR Estimate   | -19° 1' 24.9"   | 47° 18' 7.5"        | 1467.4 meters          |
| Difference       | -2.0"           | -2.7"               | 10.6 meters            |



- 1 OPTICAL ESTIMATE - SAO M1 GRAVITY
- 2 GRARR ESTIMATE - SAO M1 GRAVITY
- 3 OPTICAL ESTIMATE - APL 3.5 GRAVITY
- 4 GRARR ESTIMATE - APL 3.5 GRAVITY
- 5 OPTICAL ESTIMATE - NWL 5E-6 GRAVITY
- 6 GRARR ESTIMATE - NWL 5E-6 GRAVITY

Figure 9. Estimated Coordinates for MADGAR

## 7.0 REFERENCES

1. "Interim Status Report on Program Development and GEOS-A Data Analysis," NASA Contract Document, Wolf Research and Development Corporation, (NAS 5-9756-44A, 55, 71), August 1967.
2. Lundquist, C. A., Veis, G., "Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth," Smithsonian Astrophys. Obs. Special Report No. 200, Vol. 1, 1966.
3. Guier, W. H., Newton, R. R., "The Earth's Gravitational Field as Deduced from the Doppler Tracking of Five Satellites," Journal of Geophysical Research, Vol. 70, No. 18, September 1965.
4. Anderle, R. J., "Computational Methods Employed in Deriving Geodetic Results from Doppler Observations of Artificial Earth Satellites," Naval Weapons Laboratory Special Report No. 1977, April 1965.
5. Lerch, F. J., Marsh, J. G., O'Neill, B., "Evaluation of the Goddard Range and Range Rate System at Rosman by Intercomparison with GEOS-I Long Arc Orbital Solutions," GSFC Document X-552-68-72, November 1967.
6. Lerch, F. J., Doll, C. E., Moss, S. J., O'Neill, B., "The Determination and Comparison of the GRARR MADGAR Site Location," GSFC Document X-552-67-540, October 1967.
7. Köhnlein, W., "The Earth's Gravitational Field as Derived from a Combination of Satellite Data with Gravity Anomalies", Paper Prepared for XIV General Assembly International Union of Geodesy and Geophysics International Association of Geodesy, October 1967.

## **APPENDIX A**

**FORCE MODELS USED IN THE  
NONAME ORBIT DETERMINATION SYSTEM**

## APPENDIX A

### FORCE MODELS USED IN THE NONAME ORBIT DETERMINATION SYSTEM

#### 1.1 FORCE MODELS

The data reduction program in its present form incorporates four force models. These are:

1. The earth gravitational field
2. The solar and lunar gravitational perturbations
3. Solar radiation pressure
4. Atmospheric drag

The program is designed such that the gravitational coefficients and pertinent physical characteristics of satellites, such as reflectivity, cross-sectional area mass, and drag coefficient can be simply changed through card input or block data statement.

#### 1.2 THE EARTH'S GRAVITATIONAL FIELD

The formulation of the geopotential used is:

$$u = \frac{GM}{r} \left\{ 1 + \sum_{n=2}^k \sum_{m=0}^n \left( \frac{a}{r} \right)^n p_n^m (\sin \phi) [C_{nm} \cos m\lambda + S_{nm} \sin m\lambda] \right\} \quad (A-1)$$

where

G            is the universal gravitational constant

M            is the mass of the earth

r            is the geocentric satellite distance

$a$  is the earth's mean equatorial radius

$\phi$  is the sub-satellite geocentric latitude

$\lambda$  is the sub-satellite east longitude

$p_n^m (\sin \phi)$  is the associated spherical harmonic of degree  $n$  and order  $m$ .

The design of the potential function requires that denormalized gravitational coefficients  $C_{n,m}$  and  $S_{n,m}$  be used. The program is presently capable of accepting coefficients up to (20,20) or any sub-set of these.

The transformation of the geopotential in earth-fixed coordinates  $(r, \phi, \lambda)$  to gravitational accelerations in inertial coordinates  $(x, y, z)$  is accomplished as follows:

$$\ddot{x}_\oplus = \frac{\partial u}{\partial r} \frac{\partial r}{\partial x} + \frac{\partial u}{\partial \phi} \frac{\partial \phi}{\partial x} + \frac{\partial u}{\partial \lambda} \frac{\partial \lambda}{\partial x}; \quad \ddot{y}_\oplus, \quad \ddot{z}_\oplus \quad (A-2)$$

where the subscript " $\oplus$ " denotes accelerations due to the earth's field.

### 1.3 SOLAR AND LUNAR GRAVITATIONAL PERTURBATIONS

The perturbations caused by a third body, e.g., the sun or moon, on a satellite orbit are treated by defining a disturbing function  $R$  (Reference 1) which can be treated as the potential function  $U$ . For the solar perturbation  $R_\odot$  takes the form

$$R_\odot = \frac{GMm_\odot}{r_\odot} \left[ \left( 1 - \frac{2r}{r_\odot} S + \frac{r^2}{r_\odot^2} \right)^{-\frac{1}{2}} - \frac{r_s}{r_\odot} \right] \quad (A-3)$$

where

$$S = \cos(\vec{r}, \vec{r}_\odot)$$

$m_\odot$  is the mass of the sun in earth masses

$\vec{r}_\odot$  is the geocentric position vector of the sun

$r_\odot$  is the geocentric distance to the sun

- $r$  is the geocentric distance to the satellite
- $\vec{r}$  is the geocentric position vector of the satellite
- $G$  is the universal gravitational constant
- $M$  is the mass of the earth

The acceleration of the satellite due to the sun is then

$$\ddot{x}_\odot = \frac{\partial R_\odot}{\partial r} \frac{\partial r}{\partial x} + \frac{\partial R_\odot}{\partial \phi} \frac{\partial \phi}{\partial x} + \frac{\partial R_\odot}{\partial \lambda} \frac{\partial \lambda}{\partial x}; \quad \ddot{y}_\odot; \quad \ddot{z}_\odot \quad (A-4)$$

where  $\phi$  and  $\lambda$  are the latitude and longitude of the satellite respectively. The lunar perturbations are found from Equation (A-3) by substituting the lunar mass and distance for those of the sun.

The lunar and solar ephemerides are computed internal to the program. These positions are computed at ten equal intervals over each five day period and least squares fit to a fourth order polynomial in time about the midpoint of the five day period. The positions of these bodies are then determined at each data point by evaluating the polynomial at the observation time.

#### 1.4 SOLAR RADIATION PRESSURE

The acceleration acting on a satellite due to solar radiation pressure is formulated as follows (Reference 2).

$$\ddot{x}_{RAD} = - \frac{AP_\odot}{m} \gamma \nu L_x; \quad \ddot{y}_{RAD}; \quad \ddot{z}_{RAD} \quad (A-5)$$

where

- $L$  is the inertial unit vector from the geocenter to the sun and whose components are  $L_x, L_y, L_z$
- $A$  is the cross sectional area of the satellite
- $m$  is the satellite mass
- $\gamma$  is a factor depending on the reflective characteristics of the satellite.

$\nu$  is the eclipse factor such that:

$$\nu = \begin{cases} 0 & \text{when satellite is in earth's shadow} \\ 1 & \text{when satellite is illuminated by the sun} \end{cases}$$

$P_{\odot}$  is the solar radiation pressure in the vicinity of the earth,

$$4.5 \times 10^{-6} \frac{\text{Newton}}{\text{m}^2}$$

At present, it is assumed that the satellite is specularly reflecting with reflectivity,  $\rho$ , and thus

$$\gamma = (1 + \rho). \quad (\text{A-6})$$

The vector  $\hat{L}$  and the eclipse factor are determined from the solar ephemeris subroutine previously described, the satellite ephemeris, and involve the approximation of a cylindrical earth shadow.

## 1.5 ATMOSPHERIC DRAG

The atmospheric decelerations are computed as follows:

$$\ddot{x}_{\text{DRAG}} = \frac{\rho C_D A v v_x}{2m}; \quad \ddot{y}_{\text{DRAG}}, \quad \ddot{z}_{\text{DRAG}} \quad (\text{A-7})$$

where

$\rho$  is the ambient atmospheric density

$C_D$  is the satellite drag coefficient

$A$  is the projected area of the satellite on a plane perpendicular to direction of motion

$m$  is the satellite mass.

The velocity vector  $\vec{v}$  given in inertial coordinates by

$$\vec{v} = v_x \hat{i} + v_y \hat{j} + v_z \hat{k} \quad (A-8)$$

can be chosen to be either the velocity relative to the atmosphere which implies that the atmosphere rotates with the earth or the inertial velocity which assumes that the atmosphere is static. Presently, the former assumption is made.

The density,  $\rho$ , is computed from the 1962 U.S. Standard Atmosphere.

#### REFERENCES

1. Kozai, Y, Smithsonian Astrophysical Observatory Special Report 22, pp. 7-10.
2. H. Koelle, Handbook of Astronautical Engineering, pp. 8-33, McGraw-Hill, 1961.

## **APPENDIX B**

### **PREPROCESSING OF OPTICAL OBSERVATIONS**

## APPENDIX B

### PREPROCESSING OF OPTICAL OBSERVATIONS

#### 2.1 PREPROCESSING OF OPTICAL DATA

The first step in the processing of optical observations is usually performed by the observing source. This consists of developing a plate or film, identifying the image or images of the satellite and the images of several reference stars whose right ascensions and declinations are well known. The initial measurements of both satellite images and reference stars consist of linear rectangular coordinates. From the knowledge of the spherical coordinates of the reference stars, the right ascensions and declinations of the satellite images may be calculated. These coordinates as received by the preprocessor may be referred to the mean equator and equinox of date, true equator and equinox of date, or mean equator and equinox of some standard epoch.

Preprocessing includes, for example in the case of the GEOS-I SAO Baker-Nunn data, updating the observations from a mean equinox and equator of 1950.0 to the true equinox and equator of date through the luni-solar precession and nutation effects, the correction for planetary aberration, and the transformation of the A-S (SAO atomic time) time tag to UTC time. It is necessary to know UT1 time when the angle between Aries and the Mean Greenwich Meridian is required. UT1 time is then calculated on the basis of the differences (UT1-UTC) as published by the U.S. Naval Observatory. In the case of active flash data, where the time is recoverable to better than 100 microseconds through the use of APL published corrections to the satellite on-board clock (Reference 1), the time tag is shifted to correspond to the center of the photographic flashing light image. This latter adjustment corresponds to a shift of 0.5 milliseconds which is equivalent to approximately 4.0 meters of satellite position.

Currently, the preprocessor transforms all right ascensions and declinations to the true equator and equinox of the epoch of the observations being processed. If the observations were originally referred to the mean equator and equinox of a particular epoch, it is only necessary to precess from that epoch to the dates of the observation. However, if they were referred to the true equator and equinox of a particular epoch, it is necessary first to transform them to the mean equator and equinox of that same epoch and then precess to the epochs of the observations.

Finally, a transformation must be made from the mean equator and equinox of the epoch of the observation to the true equator and equinox of the epoch of the observation.

## 2.2 NUTATION

The transformations from the true equator and equinox of date to the mean equator and equinox of date is

$$Y = NX \quad (B-1)$$

where

$$Y = \begin{bmatrix} \cos \delta_m & \cos \alpha_m \\ \cos \delta_m & \sin \alpha_m \\ \sin \delta_m \end{bmatrix} \quad (B-2)$$

$$X = \begin{bmatrix} \cos \delta_T & \cos \alpha_T \\ \cos \delta_T & \sin \alpha_T \\ \sin \delta_T \end{bmatrix} \quad (B-3)$$

$$N = \begin{bmatrix} 1 & + \Delta\psi \cos \epsilon_m & + \Delta\psi \sin \epsilon_m \\ - \Delta\psi \cos \epsilon_m & 1 & + \Delta\epsilon \\ - \Delta\psi \sin \epsilon_m & - \Delta\epsilon & 1 \end{bmatrix} \quad (B-4)$$

where

$\alpha_m, \delta_m$  = right ascension and declination referred to mean equator and equinox of date

$\alpha_T, \delta_T$  = right ascension and declination referred to true equator and equinox of date

$\epsilon_m$  = mean obliquity of date

$\Delta\psi$  = nutation in longitude

$\Delta\epsilon$  = nutation in obliquity.

The inverse transformation is simply:

$$X = N^{-1} Y = N^T Y \quad (B-5)$$

### 2.3 PRECESSION

The transformation from the mean equator and equinox of 1950.0 to the mean equator and equinox of an arbitrary epoch  $t_1$  is

$$Y = PX \quad (B-6)$$

where

$$Y = \begin{bmatrix} \cos \delta_{t_1} & \cos \alpha_{t_1} \\ \cos \delta_{t_1} & \sin \alpha_{t_1} \\ \sin \delta_{t_1} \end{bmatrix} \quad (B-7)$$

$$X = \begin{bmatrix} \cos \delta_{1950.0} & \cos \alpha_{1950.0} \\ \cos \delta_{1950.0} & \sin \alpha_{1950.0} \\ \sin \delta_{1950.0} \end{bmatrix} \quad (B-8)$$

$$P = \begin{bmatrix} (\cos z \cos \theta \cos \zeta - \sin z \sin \zeta) & (-\cos z \cos \theta \sin \zeta - \sin z \cos \zeta) & (-\cos z \sin \theta) \\ (\sin z \cos \theta \cos \zeta + \cos z \sin \zeta) & (-\sin z \cos \theta \sin \zeta + \cos z \cos \zeta) & (-\sin z \sin \theta) \\ (\sin \theta \cos \zeta) & (-\sin \theta \sin \zeta) & (\cos \theta) \end{bmatrix} \quad (B-9)$$

The inverse transformation is

$$X = P^{-1}Y = P^T Y \quad (B-10)$$

Since the expression for  $z$ ,  $\theta$ ,  $\zeta$  are tied to 1950.0 as an epoch, the precession between 2 different epochs, neither of which is 1950.0, must be performed in two steps, using 1950.0 as an intermediary epoch.

#### REFERENCES

1. Applied Physics Laboratory (APL), "GEOS-A Clock Calibration" John Hopkins University, TSSD 186, Silver Spring, Maryland, 1966.

## **APPENDIX C**

### **TRACKING STATION COORDINATES**

## APPENDIX C

### TRACKING STATION COORDINATES

#### 1.0 DATUM PARAMETERS AND STATION COORDINATES

For the purpose of long arc satellite data reduction and intercomparison, all GEOS-I participating tracking stations have been transformed to a common datum. The common datum selected is the SAO Standard Earth C-5 Model (Reference 1) in which the Baker-Nunn station positions are used as the controlling stations for all other stations to be transformed. The semi-major axis and flattening coefficient for the SAO C-5 Earth Model are 6378165 meters and 298.25 respectively. Descriptions and formulations to effect the transformations from major and isolated datums are presented in Reference 2. The transformation of local datum station coordinates to a common center of mass reference system is important to be performed since the datum shifts are quite large. For example, on the North American datum the center of mass shift to the C-5 Standard Earth is approximately 250 meters. The center of mass coordinates of the SAO C-5 Baker-Nunn stations are assessed by SAO to have approximately 20 meter accuracy.

In order to effect any transformation, the parameters of the original datums must be known as well as the geodetic latitude, longitude and height. Table I provides a listing of the original datums and their parameters on which the stations were originally surveyed. Tables II to XI list alternately the original surveyed ellipsoidal positions and the SAO C-5 ellipsoidal positions for over 100 GEOS-I tracking stations that have been used in the long arc intercomparison effort. These tables contain symbols designating the source of original station coordinates. The symbols are defined in Section 2.0 with a list of source information. The C-5 positions for 1TANAN and MADGAR (Reference 3) have been derived by the station estimation technique contained in the Orbit Determination Program NONAME. Tables XII to XXI provide a listing of the proper station names from which the six letter designations have been derived.

Table I  
Parameters of Original Datums

| Datum Name            | Semi-Major Axis<br>(meters) | 1/f      |
|-----------------------|-----------------------------|----------|
| North American (N.A.) | 6378206.4                   | 294.9787 |
| European              | 6378388.0                   | 297.0    |
| Tokyo                 | 6377397.2                   | 299.1528 |
| Argentina             | 6378388.0                   | 297.0    |
| Mercury               | 6378166.0                   | 298.3    |
| Madagascar            | 6378388.0                   | 297.0    |
| Australian Nat'l.     | 6378160.0                   | 298.25   |
| Old Hawaiian          | 6378206.4                   | 294.9787 |
| Indian                | 6377276.3                   | 300.8017 |
| Arc (Cape)            | 6378249.1                   | 293.4663 |
| 1966 Canton Astro     | 6378388.0                   | 297.0    |
| Johnston Island       |                             |          |
| 1961                  | 6378388.0                   | 297.0    |
| Midway Astro 1961     | 6378388.0                   | 297.0    |
| Navy Iben Astro       |                             |          |
| 1947                  | 6378206.4                   | 294.9787 |
| Provisional DOS       | 6378388.0                   | 297.0    |
| Astro 1962, 65        |                             |          |
| Allen Sodano Lt.      | 6378388.0                   | 297.0    |
| 1966 SECOR ASTRO      | 6378388.0                   | 297.0    |
| Viti Levu 1916        | 6378249.1                   | 293.4663 |
| CORREGO ALEGRE        | 6378206.4                   | 294.9787 |
| USGS 1962 ASTRO       | 6378206.4                   | 294.9787 |
| BERNE                 | 6377397.2                   | 299.1528 |

Table II  
SAO — Optical — Source A

| Source | Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum        |
|--------|--------|-------------|--------------|---------------|--------------------------|--------------|
|        | 1ORGAN | 9001        | 32°25'24"!56 | 253°26'51"!17 | 1649                     | N.A.         |
|        |        |             | 32 25 24.70  | 253 26 48.29  | 1610                     | C-5          |
|        | 1OLFAN | 9002        | -25 57 33.85 | 28 14 53.91   | 1562                     | Arc (Cape)   |
|        |        |             | -25 57 37.67 | 28 14 51.45   | 1560                     | C-5          |
|        | WOOMER | 9003        | -31 06 07.26 | 136 46 58.70  | 185                      | Australian   |
|        |        |             | -31 06 04.14 | 136 47 01.93  | 158                      | C-5          |
|        | 1SPAIN | 9004        | 36 27 51.24  | 353 47 41.47  | 7                        | European     |
|        |        |             | 36 27 46.68  | 353 47 36.55  | 56                       | C-5          |
|        | 1TOKYO | 9005        | 35 40 11.08  | 139 32 28.22  | 58                       | Tokyo        |
|        |        |             | 35 40 23.03  | 139 32 16.42  | 84                       | C-5          |
|        | 1NATOL | 9006        | 29 21 38.90  | 79 27 25.61   | 1847                     | European     |
|        |        |             | 29 21 34.38  | 79 27 27.05   | 1855                     | C-5          |
|        | 1QUIPA | 9007        | -16 28 05.09 | 288 30 22.84  | 2600                     | N.A.         |
|        |        |             | -16 27 58.04 | 288 30 24.02  | 2479                     | C-5          |
|        | 1SHRAZ | 9008        | 29 38 17.96  | 52 31 11.80   | 1578                     | European     |
|        |        |             | 29 38 13.59  | 52 31 11.20   | 1561                     | C-5          |
|        | 1CURAC | 9009        | 12 05 21.55  | 291 09 42.55  | 23                       | N.A.         |
|        |        |             | 12 05 24.93  | 291 09 43.97  | -33                      | C-5          |
|        | 1JUPTR | 9010        | 27 01 13.00  | 279 53 12.92  | 26                       | N.A.         |
|        |        |             | 27 01 14.23  | 279 53 12.95  | -36                      | C-5          |
|        | 1VILDO | 9011        | -31 56 36.53 | 294 53 39.82  | 598                      | Argentinean  |
|        |        |             | -31 56 36.35 | 294 53 36.11  | 636                      | C-5          |
|        | 1MAUIO | 9012        | 20 42 37.49  | 203 44 24.11  | 3027                     | Old Hawaiian |
|        |        |             | 20 42 25.66  | 203 44 33.23  | 3027                     | C-5          |

Table II (Continued)

| Source | Name    | Station No. | Latitude                      | Longitude                     | Geodetic Height (meters) | Datum             |
|--------|---------|-------------|-------------------------------|-------------------------------|--------------------------|-------------------|
| A      | AUSBAK  | 9023        | -31°23'30".82<br>-31 23 27.69 | 136°52'39".02<br>136 52 42.23 | 164<br>137               | Australian<br>C-5 |
| A      | OSLONR  | 9426        | 60 12 40.38<br>60 12 38.88    | 10 45 08.74<br>10 45 02.26    | 585<br>573               | European<br>C-5   |
| I      | NATALB* | 9029        | -05 55 50.00<br>-05 55 43.49  | 324 50 18.00<br>324 50 21.30  | 112<br>45                | N.A.<br>C-5       |
| D      | AGASSI* | 9050        | 42 30 20.97<br>42 30 20.51    | 288 26 28.71<br>288 26 29.79  | 193<br>138               | N.A.<br>C-5       |
| I      | COLDLK* | 9424        | 54 44 38.02<br>54 44 37.26    | 249 57 25.85<br>249 57 21.90  | 597<br>548               | N.A.<br>C-5       |
| I      | EDWAFB* | 9425        | 34 57 50.68<br>34 57 50.17    | 242 05 11.39<br>242 05 07.80  | 784<br>754               | N.A.<br>C-5       |
| I      | RIGLAT* | 9428        | 56 56 54.00<br>56 56 52.37    | 24 03 42.00<br>24 03 37.49    | 5<br>-15                 | European<br>C-5   |
| I      | POTDAM* | 9429        | 52 22 55.00<br>52 22 52.33    | 13 04 01.00<br>13 03 55.80    | 111<br>106               | European<br>C-5   |
| I      | ZVENIG* | 9430        | 55 41 37.70<br>55 41 36.17    | 36 46 03.00<br>36 46 00.17    | 145<br>114               | European<br>C-5   |

\*These SAO station positions were derived by using the weighting scheme described in Reference 2, Section 2.

Table III  
STADAN — Optical — Source B

| Name   | Station No. | Latitude                     | Longitude                     | Geodetic Height (meters) | Datum             |
|--------|-------------|------------------------------|-------------------------------|--------------------------|-------------------|
| 1BPOIN | 1021        | 38°25'49".63<br>38 25 49.44  | 282°54'48".23<br>282 54 48.65 | 5<br>-50                 | N.A.<br>C-5       |
| 1FTMYR | 1022        | 26 32 51.89<br>26 32 53.08   | 278 08 03.93<br>278 08 03.80  | 19<br>-42                | N.A.<br>C-5       |
| 1OOMER | 1024        | -31 23 30.07<br>-31 23 26.96 | 136 52 11.05<br>136 52 14.25  | 152<br>148               | Australian<br>C-5 |
| 1QUITO | 1025        | -0 37 28.00<br>-0 37 22.63   | 281 25 14.81<br>281 25 15.23  | 3649<br>3554             | N.A.<br>C-5       |
| 1LIMAP | 1026        | -11 46 44.43<br>-11 46 37.56 | 282 50 58.23<br>282 50 58.86  | 155<br>34                | N.A.<br>C-5       |
| 1SATAG | 1028        | -33 09 07.66<br>-33 08 58.76 | 289 19 51.35<br>289 19 52.59  | 922<br>705               | N.A.<br>C-5       |
| 1MOJAV | 1030        | 35 19 48.09<br>35 19 47.57   | 243 06 02.73<br>243 05 59.18  | 905<br>874               | N.A.<br>C-5       |
| 1JOBUR | 1031        | -25 52 58.86<br>-25 53 02.70 | 27 42 27.93<br>27 42 25.41    | 1530<br>1546             | ARC (Cape)<br>C-5 |
| 1NEWFL | 1032        | 47 44 29.74<br>47 44 28.73   | 307 16 43.37<br>307 16 46.67  | 104<br>58                | N.A.<br>C-5       |
| 1COLEG | 1033        | 64 52 19.72<br>64 52 17.78   | 212 09 47.17<br>212 09 37.29  | 162<br>139               | N.A.<br>C-5       |
| 1GFORK | 1034        | 48 01 21.40<br>48 01 20.81   | 262 59 21.56<br>262 59 19.55  | 253<br>200               | N.A.<br>C-5       |
| 1WNKFL | 1035        | 51 26 44.12<br>51 26 40.67   | 359 18 14.62<br>359 18 08.35  | 62<br>76                 | European<br>C-5   |

Table III (Continued)

| Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum      |
|--------|-------------|--------------|---------------|--------------------------|------------|
| 1ROSMA | 1042        | 35°12'06".93 | 277°07'41".01 | 914                      | N.A.       |
|        |             | 35 12 07.03  | 277 07 40.81  | 857                      | C-5        |
| 1TANAN | 1043        | -19 00 27.09 | 47 18 00.46   | 1377                     | Tananarive |
|        |             | -19 00 33.26 | 47 17 58.89   | 1355                     | C-5        |

Table IV  
STADAN — R/R — Source B

| Name   | Station No. | Latitude      | Longitude     | Geodetic Height (meters) | Datum      |
|--------|-------------|---------------|---------------|--------------------------|------------|
| CARVON | 1152        | -24°54'14".85 | 113°42'55".05 | 38                       | Australian |
|        |             | -24 54 12.29  | 113 42 58.54  | 10                       | C-5        |
| ROSRAN | 1126        | 35 11 45.05   | 277 07 26.23  | 880                      | N.A.       |
|        |             | 35 11 45.15   | 277 07 26.02  | 823                      | C-5        |
| MADGAR | 1122        | -19 01 13.32  | 47 18 09.45   | 1403                     | Tananarive |
|        |             | -19 01 19.41  | 47 18 07.96   | 1382                     | C-5        |

Table V  
NAVY TRANET — Doppler — Source C

| Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum              |
|--------|-------------|--------------|---------------|--------------------------|--------------------|
| LASHAM | 2006        | 51°11'10".62 | 358°58'30".51 | 182                      | European           |
|        |             | 51 11 07.12  | 358 58 24.25  | 196                      | C-5                |
| SANHES | 2008        | -23 13 01.74 | 314 07 50.59  | 608*                     | Correga Alegre     |
|        |             | -23 13 01.74 | 314 07 50.59  | 608                      | C-5                |
| PHILIP | 2011        | 14 58 57.79  | 120 04 25.98  | 8                        | Tokyo              |
|        |             | 14 59 16.42  | 120 04 21.61  | -70                      | C-5                |
| SMTHFD | 2012        | -34 40 31.31 | 138 39 12.39  | 39                       | Australian         |
|        |             | -34 40 28.16 | 138 39 15.66  | 31                       | C-5                |
| MISAWA | 2013        | 40 43 04.63  | 141 20 04.69  | -10                      | Tokyo              |
|        |             | 40 43 14.63  | 141 19 51.45  | 38                       | C-5                |
| ANCHOR | 2014        | 61 17 01.98  | 210 10 37.46  | 61                       | N.A.               |
|        |             | 61 16 59.60  | 210 10 28.60  | 44                       | C-5                |
| TAFUNA | 2017        | -14 19 50.19 | 189 17 13.96  | 6*                       | USGS<br>1962 Astro |
|        |             | -14 19 50.19 | 189 17 13.96  | 6                        | C-5                |
| THULEG | 2018        | 76 32 18.62  | 291 13 46.72  | 43                       | N.A.               |
|        |             | 76 32 20.72  | 291 13 51.07  | -7                       | C-5                |
| MCMRDO | 2019        | -77 50 51.00 | 166 40 25.00  | -43                      | Mercury            |
|        |             | -77 50 50.58 | 166 40 35.02  | -29                      | C-5                |
| WAHIWA | 2100        | 21 31 26.86  | 202 00 00.63  | 380                      | Old Hawaiian       |
|        |             | 21 31 14.95  | 202 00 09.83  | 368                      | C-5                |
| LACRES | 2103        | 32 16 43.75  | 253 14 48.25  | 1201                     | N.A.               |
|        |             | 32 16 43.91  | 253 14 45.34  | 1162                     | C-5                |

\*MSL

Table V (Continued)

| Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum    |
|--------|-------------|--------------|---------------|--------------------------|----------|
| LASHM2 | 2106        | 51°11'12".32 | 358°58'30".21 | 187                      | European |
|        |             | 51 11 08.82  | 358 58 23.95  | 201                      | C-5      |
| APLMND | 2111        | 39 09 47.83  | 283 06 11.07  | 146                      | N.A.     |
|        |             | 39 09 47.60  | 283 06 11.52  | 90                       | C-5      |
| PRETOR | 2115        | -25 56 46.09 | 28 20 53.00   | 1417                     | European |
|        |             | -25 56 49.97 | 28 20 50.67   | 1595                     | C-5      |
| SHEMYA | 2739        | 52 43 01.52  | 174 06 51.43  | 44                       | N.A.     |
|        |             | 52 42 56.52  | 174 06 44.17  | 89                       | C-5      |
| BELTSV | 2742        | 39 01 39.46  | 283 10 27.25  | 50                       | N.A.     |
|        |             | 39 01 39.23  | 283 10 27.72  | -5                       | C-5      |
| STNVIL | 2745        | 33 25 31.57  | 269 09 10.70  | 44                       | N.A.     |
|        |             | 33 25 31.76  | 269 09 09.66  | -10                      | C-5      |

Table VI  
AIR FORCE — Optical — Source I

| Source | Name    | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum |
|--------|---------|-------------|--------------|---------------|--------------------------|-------|
| E      | ANTIGA  | 3106        | 17°08'51".68 | 298°12'37".41 | 7                        | N.A.  |
|        |         |             | 17 08 53.88  | 298 12 39.19  | -42                      | C-5   |
|        | GRNVLE  | 3333        | 33 28 48.97  | 268 59 49.17  | 45                       | N.A.  |
|        |         |             | 33 28 49.15  | 268 59 48.12  | -9                       | C-5   |
|        | GRVILL  | 3334        | 33 25 31.95  | 269 05 11.35  | 43                       | N.A.  |
|        |         |             | 33 25 32.14  | 269 05 10.30  | -10                      | C-5   |
|        | USAFAAC | 3400        | 39 00 22.44  | 255 07 01.01  | 2191                     | N.A.  |
|        |         |             | 39 00 21.99  | 255 06 58.32  | 2147                     | C-5   |
|        | BEDFRD  | 3401        | 42 27 17.53  | 288 43 35.03  | 88                       | N.A.  |
|        |         |             | 42 27 17.06  | 288 43 36.14  | 33                       | C-5   |
|        | SEMMES  | 3402        | 30 46 49.35  | 271 44 52.37  | 79                       | N.A.  |
|        |         |             | 30 46 49.85  | 271 44 51.64  | 23                       | C-5   |
|        | SWANIS  | 3404        | 17 24 16.57  | 276 03 29.87  | 83                       | N.A.  |
|        |         |             | 17 24 18.90  | 276 03 29.71  | 18                       | C-5   |
|        | GRDTRK  | 3405        | 21 25 47.05  | 288 51 14.03  | 7                        | N.A.  |
|        |         |             | 21 25 48.69  | 288 51 15.03  | -48                      | C-5   |
|        | CURACO  | 3406        | 12 05 22.11  | 291 09 43.76  | 23                       | N.A.  |
|        |         |             | 12 05 25.49  | 291 09 45.16  | -34                      | C-5   |
|        | TRNDAD  | 3407        | 10 44 32.78  | 298 23 23.67  | 269                      | N.A.  |
|        |         |             | 10 44 36.16  | 298 23 25.43  | 210                      | C-5   |
|        | GRANFK  | 3451        | 47 56 38.63  | 262 37 11.21  | 296                      | N.A.  |
|        |         |             | 47 56 38.03  | 262 37 09.15  | 242                      | C-5   |
|        | TWINOK  | 3452        | 36 07 25.69  | 262 47 04.48  | 312                      | N.A.  |
|        |         |             | 36 07 25.58  | 262 47 02.68  | 262                      | C-5   |

Table VI (Continued)

| Source | Name   | Station No. | Latitude     | Longitude    | Geodetic Height (meters) | Datum    |
|--------|--------|-------------|--------------|--------------|--------------------------|----------|
| E      | ROTHGR | 3453        | 51°25'00".00 | 9°30'06".00  | 351                      | European |
|        |        |             | 51 24 57.05  | 9 30 00.58   | 352                      | C-5      |
|        | ATHNGR | 3463        | 37 53 30.00  | 23 44 30.00  | 16                       | European |
|        |        |             | 37 53 26.07  | 23 44 26.73  | 23                       | C-5      |
|        | TORRSP | 3464        | 40 29 18.53  | 356 34 41.24 | 588                      | European |
|        |        |             | 40 29 14.10  | 356 34 36.06 | 635                      | C-5      |
|        | CHOFUJ | 3465        | 35 39 57.00  | 139 32 12.00 | 49                       | Tokyo    |
|        |        |             | 35 40 08.96  | 139 32 00.19 | 75                       | C-5      |
|        | KINDLY | 3471        | 32 22 57.30  | 295 19 00.46 | 26                       | N.A.     |
|        |        |             | 32 22 57.41  | 295 19 02.09 | -23                      | C-5      |
|        | HUNTER | 3648        | 32 00 05.87  | 278 50 46.36 | 17                       | N.A.     |
|        |        |             | 32 00 06.32  | 278 50 46.32 | -40                      | C-5      |
|        | JUPRAF | 3649        | 27 01 14.80  | 279 53 13.72 | 26                       | N.A.     |
|        |        |             | 27 01 16.02  | 279 53 13.72 | -37                      | C-5      |
|        | ABERDN | 3657        | 39 28 18.97  | 283 55 44.56 | 4                        | N.A.     |
|        |        |             | 39 28 18.71  | 283 55 45.10 | -51                      | C-5      |
|        | HOMEST | 3861        | 25 30 24.69  | 279 36 42.69 | 18                       | N.A.     |
|        |        |             | 25 30 26.02  | 279 36 42.70 | -44                      | C-5      |
|        | CHYWYN | 3902        | 41 07 59.20  | 255 08 02.65 | 1890                     | N.A.     |
|        |        |             | 41 07 58.61  | 255 07 59.94 | 1845                     | C-5      |

Table VII  
ARMY MAP SERVICE — SECOR — Source H

| Source | Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum                           |
|--------|--------|-------------|--------------|---------------|--------------------------|---------------------------------|
| G      | HERNDN | 5001        | 38°59'37".69 | 282°40'16".68 | 119                      | N.A.                            |
|        |        |             | 38 59 37.47  | 282 40 17.08  | 64                       | C-5                             |
| I      | CUBCAL | 5200        | 32 48 00.00  | 242 52 00.00  | 101                      | N.A.                            |
|        |        |             | 32 47 59.74  | 242 51 56.55  | 71                       | C-5                             |
| I      | LARSON | 5201        | 47 11 00.00  | 240 40 00.00  | 354                      | N.A.                            |
|        |        |             | 47 10 58.76  | 240 39 55.68  | 319                      | C-5                             |
| I      | WRGTON | 5202        | 43 39 00.00  | 264 25 00.00  | 481                      | N.A.                            |
|        |        |             | 43 38 59.49  | 264 24 58.27  | 428                      | C-5                             |
| G      | GREENV | 5333        | 33 25 32.34  | 269 05 10.78  | 43                       | N.A.                            |
|        |        |             | 33 25 32.53  | 269 05 09.73  | -10                      | C-5                             |
| TRUKIS |        | 5401        | 7 27 39.30   | 151 50 31.28  | 5*                       | Navy Iben Astro 1947            |
|        |        |             | 7 27 39.30   | 151 50 31.28  | 5                        | C-5                             |
| SWALLO |        | 5402        | -10 18 21.42 | 166 17 56.79  | 9*                       | 1966 SECOR Astro                |
|        |        |             | -10 18 21.42 | 166 17 56.79  | 9                        | C-5                             |
| KUSAIE |        | 5403        | 5 17 44.43   | 163 01 29.88  | 7*                       | Astro 1962, 65, Allen Sodano Lt |
|        |        |             | 5 17 44.43   | 163 01 29.88  | 7                        | C-5                             |
| GIZZOO |        | 5404        | -8 05 40.58  | 156 49 24.82  | 49*                      | Provisional DOS                 |
|        |        |             | -8 05 40.58  | 156 49 24.82  | 49                       | C-5                             |

\* MSL

Table VII (Continued)

| Source | Name   | Station No. | Latitude     | Longitude    | Geodetic Height (meters) | Datum                |
|--------|--------|-------------|--------------|--------------|--------------------------|----------------------|
|        | TARAWA | 5405        | 1°21'42.13   | 172°55'47.26 | 7*                       | 1966 SECOR Astro     |
|        | NANDIS | 5406        | 1 21 42.13   | 172 55 47 26 | 7                        | C-5                  |
|        | CANTON | 5407        | -17 45 31.01 | 177 27 02.83 | 17*                      | Viti Levu 1916       |
|        | JONSTN | 5408        | -2 46 28.90  | 188 16 43.47 | 17                       | C-5                  |
|        | MIDWAY | 5410        | -2 46 28.90  | 188 16 43.47 | 6*                       | 1966 Canton Astro    |
|        | MAUIHI | 5411        | 16 43 51.68  | 190 28 41.55 | 6                        | Johnston Island 1961 |
|        | FTWART | 5648        | 16 43 51.68  | 190 28 41.55 | 6*                       | Midway Astro 1961    |
|        | HNTAFB | 5649        | 28 12 32.06  | 182 37 49.53 | 6                        | C-5                  |
|        | HOMEFL | 5861        | 28 12 32.06  | 182 37 49.53 | 32                       | Old Hawaiian         |
|        |        |             | 20 49 37.00  | 203 31 52.77 | 31                       | C-5                  |
| G      |        |             | 20 49 25.14  | 203 32 01.88 | 29                       | N.A.                 |
| G      |        |             | 31 55 18.41  | 278 26 00.26 | -27                      | C-5                  |
| G      |        |             | 31 55 18.86  | 278 26 00.18 | 27                       | N.A.                 |
| G      |        |             | 32 00 04.04  | 278 50 43.17 | -30                      | C-5                  |
| G      |        |             | 32 00 04.49  | 278 50 43.13 | 18                       | N.A.                 |
|        |        |             | 25 29 21.18  | 279 37 39.35 | -44                      | C-5                  |
|        |        |             | 25 29 22.51  | 279 37 39.37 |                          |                      |

\*MSL

Table VIII  
USC&GS — Optical — Source F

| Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum |
|--------|-------------|--------------|---------------|--------------------------|-------|
| BELTVL | 6002        | 39°01'39".03 | 283°10'26".94 | 45                       | N.A.  |
|        |             | 39 01 38.80  | 283 10 27.40  | -10                      | C-5   |
| ASTRMD | 6100        | 39 01 39.72  | 283 10 27.83  | 45                       | N.A.  |
|        |             | 39 01 39.49  | 283 10 28.29  | -10                      | C-5   |
| TIMINS | 6113        | 48 33 56.17  | 278 37 44.54  | 290                      | N.A.  |
|        |             | 48 33 55.70  | 278 37 44.49  | 232                      | C-5   |

Table IX  
SPEOPT — Optical — Source B

| Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum |
|--------|-------------|--------------|---------------|--------------------------|-------|
| 1UNDAK | 7034        | 48°01'21".40 | 262°59'21".56 | 255                      | N.A.  |
|        |             | 48 01 20.81  | 262 59 19.55  | 201                      | C-5   |
| 1EDINB | 7036        | 26 22 45.44  | 261 40 09.03  | 67                       | N.A.  |
|        |             | 26 22 46.35  | 261 40 07.34  | 15                       | C-5   |
| 1COLBA | 7037        | 38 53 36.07  | 267 47 42.12  | 271                      | N.A.  |
|        |             | 38 53 35.81  | 267 47 40.85  | 218                      | C-5   |
| 1BERMD | 7039        | 32 21 48.83  | 295 20 32.56  | 21                       | N.A.  |
|        |             | 32 21 48.94  | 295 20 34.18  | -28                      | C-5   |
| 1PURIO | 7040        | 18 15 26.22  | 294 00 22.17  | 58                       | N.A.  |
|        |             | 18 15 28.30  | 294 00 23.63  | 5                        | C-5   |

Table IX (Continued)

| Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum |
|--------|-------------|--------------|---------------|--------------------------|-------|
| 1GSFCP | 7043        | 39°01'15".01 | 283°10'19".93 | 54                       | N.A.  |
|        |             | 39 01 14.78  | 283 10 20.39  | -1                       | C-5   |
| 1CKVLE | 7044        | 38 22 12.50  | 274 21 16.81  | 187                      | N.A.  |
|        |             | 38 22 12.33  | 274 21 16.28  | 131                      | C-5   |
| 1DENVR | 7045        | 39 38 48.03  | 255 23 41.19  | 1796                     | N.A.  |
|        |             | 39 38 47.54  | 255 23 38.52  | 1751                     | C-5   |
| 1JUM24 | 7071        | 27 01 12.77  | 279 53 12.31  | 25                       | N.A.  |
|        |             | 27 01 14.00  | 279 53 12.30  | -38                      | C-5   |
| 1JUM40 | 7072        | 27 01 13.17  | 279 53 12.49  | 25                       | N.A.  |
|        |             | 27 01 14.39  | 279 53 12.49  | -38                      | C-5   |
| 1JUPC1 | 7073        | 27 01 13.11  | 279 53 12.72  | 22                       | N.A.  |
|        |             | 27 01 14.33  | 279 53 12.72  | -41                      | C-5   |
| 1JUBC4 | 7074        | 27 01 13.33  | 279 53 12.76  | 25                       | N.A.  |
|        |             | 27 01 14.55  | 279 53 12.76  | -38                      | C-5   |
| 1SUDBR | 7075        | 46 27 20.99  | 279 03 10.35  | 281                      | N.A.  |
|        |             | 46 27 20.52  | 279 03 10.35  | 224                      | C-5   |
| 1JAMAC | 7076        | 18 04 31.98  | 283 11 26.52  | 485                      | N.A.  |
|        |             | 18 04 34.20  | 283 11 27.03  | 423                      | C-5   |

Table X  
SPEOPT — Laser — Source B

| Name   | Station No. | Latitude     | Longitude     | Geodetic Height (meters) | Datum |
|--------|-------------|--------------|---------------|--------------------------|-------|
| ROSLAS | 7051        | 35°11'46".60 | 277°07'26".23 | 879                      | N.A.  |
|        |             | 35 11 46.70  | 277 07 26.02  | 822                      | C-5   |
| GODLAS | 7050        | 39 01 13.68  | 283 10 18.05  | 55                       | N.A.  |
|        |             | 39 01 13.45  | 283 10 18.51  | 0                        | C-5   |

Table XI  
INTERNATIONAL — Optical — Source I

| Source | Name   | Station No. | Latitude     | Longitude    | Geodetic Height (meters) | Datum    |
|--------|--------|-------------|--------------|--------------|--------------------------|----------|
| D      | DELFTH | 8009        | 52°00'09".24 | 4°22'21".23  | 23                       | European |
|        |        |             | 52 00 06.12  | 4 22 15.30   | 28                       | C-5      |
|        | MALVRN | 8011        | 52 08 39.12  | 358 01 59.49 | 111                      | European |
|        |        |             | 52 08 35.68  | 358 01 53.03 | 125                      | C-5      |
|        | ZIMWLD | 8010        | 46 52 41.77  | 7 27 57.56   | 898                      | BERNE    |
|        |        |             | 46 52 36.73  | 7 27 52.54   | 907                      | C-5      |

Table XII  
SAO — optical

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>               |
|-------------|--------------------|-------------------------------|
| 1ORGAN      | 9001               | Organ Pass, New Mexico        |
| 1OLFAN      | 9002               | Olifantsfontein, South Africa |
| 1OOMER      | 9003               | Woomera, Australia            |
| 1SPAIN      | 9004               | San Fernando, Spain           |
| 1TOKYO      | 9005               | Tokyo, Japan                  |
| 1NATOL      | 9006               | Naini Tal, India              |
| 1QUIPA      | 9007               | Arequipa, Peru                |
| 1SHRAZ      | 9008               | Shiraz, Iran                  |
| 1CURAC      | 9009               | Curacao, Lesser Antilles      |
| 1JUPTR      | 9010               | Jupiter, Florida              |
| 1VILDO      | 9011               | Villa Dolores, Argentina      |
| 1MAUTO      | 9012               | Maui, Hawaii                  |
| OSLONR      | 9426               | Oslo, Norway                  |
| AUSBAK      | 9023               | Woomera, Australia            |
| NATALB      | 9029               | Natal, Brazil                 |
| AGASSI      | 9050               | Cambridge, Massachusetts      |
| COLDLK      | 9424               | Cold Lake, Alberta            |
| EDWAFB      | 9425               | Edwards AFB, California       |
| RIGLAT      | 9428               | Riga, Latvia                  |
| POTDAM      | 9429               | Potsdam, Germany              |
| ZVENIG      | 9430               | Zvenigorod, Russia            |

Table XIII  
STADAN — Optical

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>                     |
|-------------|--------------------|-------------------------------------|
| 1BPOIN      | 1021               | Blossom Point, Maryland             |
| 1FTMYR      | 1022               | Fort Myers, Florida                 |
| 1OOMER      | 1024               | Woomera, Australia                  |
| 1QUITO      | 1025               | Quito, Ecuador                      |
| 1LIMAP      | 1026               | Lima, Peru                          |
| 1SATAG      | 1028               | Santiago, Chile                     |
| 1MOJAV      | 1030               | Mojave, California                  |
| 1JOBUR      | 1031               | Johannesburg, Union of South Africa |
| 1NEWFL      | 1032               | St. John's, Newfoundland            |
| 1COLEG      | 1033               | College, Alaska                     |
| 1GFORK      | 1034               | East Grand Forks, Minnesota         |
| 1WNKFL      | 1035               | Winkfield, England                  |
| 1ROSMA      | 1042               | Rosman, North Carolina              |
| 1TANAN      | 1043               | Tananarive, Madagascar              |

Table XIV  
STADAN — R/R

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>        |
|-------------|--------------------|------------------------|
| CARVON      | 1152               | Carnarvon, Australia   |
| ROSMAN      | 1126               | Rosman, North Carolina |
| MADGAR      | 1122               | Tananarive, Madagascar |

Table XV  
NAVY TRANET — Doppler

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>                 |
|-------------|--------------------|---------------------------------|
| LASHAM      | 2006               | Lasham, England                 |
| SANHES      | 2008               | Sao Jose dos Campos, Brazil     |
| PHILIP      | 2011               | San Miquel, Philippines         |
| SMTHFD      | 2012               | Smithfield, Australia           |
| MISAWA      | 2013               | Misawa, Japan                   |
| ANCHOR      | 2014               | Anchorage, Alaska               |
| TAFUNA      | 2017               | Tafuna, American Samoa          |
| THULEG      | 2018               | Thule, Greenland                |
| MCMRDO      | 2019               | McMurdo Sound, Antarctica       |
| WAHIWA      | 2100               | South Point, Hawaii             |
| LACRES      | 2103               | Las Cruces, New Mexico          |
| LASHM2      | 2106               | Lasham, England                 |
| APLMND      | 2111               | APL Howard County, Maryland     |
| PRETOR      | 2115               | Pretoria, Union of South Africa |
| SHEMYA      | 2739               | Shemya Island, Alaska           |
| BELTSV      | 2742               | Beltsville, Maryland            |
| STNVIL      | 2745               | Stoneville, Mississippi         |

Table XVI  
AIR FORCE — Optical

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>                    |
|-------------|--------------------|------------------------------------|
| ANTIGA      | 3106               | Antigua Island, Lesser Antilles    |
| GRNVLE      | 3333               | Stoneville, Mississippi            |
| GRVILL      | 3334               | Stoneville, Mississippi            |
| USAFAC      | 3400               | Colorado Springs, Colorado         |
| BEDFRD      | 3401               | L. G. Hanscom Field, Massachusetts |
| SEMMES      | 3402               | Semmes Island, Georgia             |
| SWANIS      | 3404               | Swan Island, Caribbean Sea         |
| GRDTRK      | 3405               | Grand Turk, Caicos Islands         |
| CURACO      | 3406               | Curacao, Lesser Antilles           |
| TRNDAD      | 3407               | Trinidad Island                    |
| GRANFK      | 3451               | Grand Forks, North Dakota          |
| TWINOK      | 3452               | Twin Oaks, Oklahoma                |
| ROTHGR      | 3453               | Rothwesten, West Germany           |
| ATHNGR      | 3463               | Athens, Greece                     |
| TORRSP      | 3464               | Torrejon de Ardoz, Spain           |
| CHOFUJ      | 3465               | Chofu, Japan                       |
| KINDLY      | 3471               | Kindly AFB, Bermuda                |
| HUNTER      | 3648               | Hunter AFB, Georgia                |
| JUPRAF      | 3649               | Jupiter, Florida                   |
| ABERDN      | 3657               | Aberdeen, Maryland                 |
| HOMEST      | 3861               | Homestead AFB, Florida             |
| CHYWYN      | 3902               | Cheyenne, Wyoming                  |

Table XVII  
ARMY MAP SERVICE — Secor

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>                    |
|-------------|--------------------|------------------------------------|
| HERNDN      | 5001               | Herndon, Virginia                  |
| CUBCAL      | 5200               | San Diego, California              |
| LARSON      | 5201               | Moses Lake, Washington             |
| WRGTON      | 5202               | Worthington, Minnesota             |
| GREENV      | 5333               | Greenville, Mississippi            |
| TRUKIS      | 5401               | Truk Island, Caroline Islands      |
| SWALLO      | 5402               | Swallow Island, Santa Cruz Islands |
| KUSAIE      | 5403               | Kusaie Islands, Caroline Island    |
| GIZZOO      | 5404               | Gizzoo, Gonzongo, Solomon Islands  |
| TARAWA      | 5405               | Tarawa, Gilbert Islands            |
| NANDIS      | 5406               | Nandi, Vitilevu, Fiji Islands      |
| CANTON      | 5407               | Canton Island, Phoenix Islands     |
| JONSTN      | 5408               | Johnston Island, Pacific Ocean     |
| MIDWAY      | 5410               | Eastern Island, Midway Islands     |
| MAUIHI      | 5411               | Maui, Hawaii                       |
| FTWART      | 5648               | Fort Stewart, Georgia              |
| HNTAFB      | 5649               | Hunter AFB, Georgia                |
| HOMEFL      | 5861               | Homestead AFB, Florida             |

Table XVIII  
USC & GS — Optical

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>      |
|-------------|--------------------|----------------------|
| BELTVL      | 6002               | Beltsville, Maryland |
| ASTRMD      | 6100               | Beltsville, Maryland |
| TIMINS      | 6113               | Timmins, Ontario     |

Table XIX  
SPEOPT — Optical

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>                                  |
|-------------|--------------------|--|
| 1UNDAK      | 7034               | Univ. North Dakota, Grand Forks,<br>North Dakota |
| 1EDINB      | 7036               | Edinburg, Texas                                  |
| 1COLBA      | 7037               | Columbia, Missouri                               |
| 1BERMD      | 7039               | Bermuda Island                                   |
| 1PURIO      | 7040               | San Juan, Puerto Rico                            |
| 1GSFCP      | 7043               | GSFC, Greenbelt, Maryland                        |
| 1CKVLE      | 7044               | Clarksville, Indiana                             |
| 1DENVR      | 7045               | Denver, Colorado                                 |
| 1JUM24      | 7071               | Jupiter, Florida                                 |
| 1JUM40      | 7072               | Jupiter, Florida                                 |
| 1JUPC1      | 7073               | Jupiter, Florida                                 |
| 1JUBC4      | 7074               | Jupiter, Florida                                 |
| 1SUDBR      | 7075               | Sudbury, Ontario                                 |
| 1JAMAC      | 7076               | Jamaica, B. W. I.                                |

Table XX  
SPEOPT — Laser

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>           |
|-------------|--------------------|---------------------------|
| ROSLAS      | 7051               | Rosman, North Carolina    |
| GODLAS      | 7050               | GSFC, Greenbelt, Maryland |

Table XXI  
INTERNATIONAL — Optical

| <u>Name</u> | <u>Station No.</u> | <u>Location</u>    |
|-------------|--------------------|--------------------|
| DELFTH      | 8009               | Delft, Holland     |
| MALVRN      | 8011               | Malvern, England   |
| ZIMWLD      | 8010               | Berne, Switzerland |

## 2.0 SOURCES

The following sources were used to obtain the original datum positions:

| <u>Symbol</u> | <u>Source</u>  |
|---------------|--|
| A             | Geodetic Parameters for a Standard Earth Obtained from Baker-Nunn Observations; September 1966; Smithsonian Astrophysical Observatory. |
| B             | Goddard Directory of Tracking Station Locations; August 1966; Goddard Space Flight Center.   |
| C             | NWL-8 Geodetic Parameters Based on Doppler Satellite Observations; July 1967; R. Anderle and S. Smith, Naval Weapons Laboratory.       |

Since the above official documents did not contain all those positions that were to be transformed, it was necessary to contact other sources for the positions of the remaining stations. These sources are:

| <u>Symbol</u> | <u>Source</u>   |
|---------------|---|
| D             | Private communication with personnel at SAO; K. Haramundanis; E. Miller; A. Girnius.              |
| E             | Private communication with 1381 Geodetic Survey Squadron, USAF; S. Tischler.                      |
| F             | Private communication with personnel at USC&GS; B. Stevens.                                       |
| G             | Private communication with personnel at U.S. Army Engineers Topographic Laboratories; L. Gambino. |
| H             | Private communication with NASA Space Science Data Center; J. Johns; D. Tidwell.                  |
| I             | General Station Data Sheet — GEOS-A-Project Manager NASA Headquarters.                            |

## REFERENCES

1. Lundquist, C. A., Veis, G., "Geodetic Parameters for a 1966 Smithsonian Institution Standard Earth," Smithsonian Astrophysical Observatory Special Report 200, Vol. 1, 1966.
2. Lerch, F. J., Marsh, J. G., D'Aria, M. D., Brooks, R. L. "Geos I Tracking Station Positions on the SAO Standard Earth (C-5)", GSFC Document X-552-68-70.
3. Lerch, F. J., Doll, C. E., Moss, S. J., O'Neill, B., "The Determination and Comparison of the GRARR MADGAR Site Location," GSFC Document X-552-67-540, October 1967.